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A Method of Schlieren Alignment Stabilization Using Automatic Feedback Control

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A METHOD OF SCHLIEREN
ALIGNMENT STABILIZATION
USING AUTOMATIC FEEDBACK CONTROL

by

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This thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the School of Photographic Arts and Sciences in the College of Graphic Arts and Photography of the Rochester Institute of Technology

Thesis advisor: John F. Carson

Certificate of Approval--Master's Thesis

School of Photographic Arts and Sciences
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Rochester, New York

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's Thesis of

W. Lawton King

with a major in Photographic Science
has been approved by the Thesis Committee as
satisfactory for the thesis requirement for the
Master of Science degree at the convocation of
June 10, 1972

Thesis Committee: ______________________
Thesis adviser

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Graduate adviser

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I also want to take this opportunity to express my gratitude to the U. S. Naval Ordnance Laboratory, its Directorate and the Employee Development Division for their confidence and financial support which permitted my program of study at Rochester Institute of Technology. Finally I wish to thank D. Max Beard without whose encouragement I would not have applied for the Laboratory's Graduate Study Program.

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ABSTRACT

An investigation of the application of feedback control to schlieren system alignment stabilization is presented. A feedback control system was designed with the necessary sensors and actuator to maintain the knife edge alignment of a schlieren system. The feedback control system's performance when subjected to controlled disturbances was evaluated. The results indicated that the approach is feasible.

INTRODUCTION

The use of schlieren as a tool in wind tunnel flow visualization dates back to the earliest work in this area. These first schlieren systems differ little in concept from those in use today. This fact may speak well of schlieren as a flow visualization technique under its earlier developers, but perhaps not so well of modern schlieren systems. The main improvements that have been made are better mechanical and optical stability through improved manufacturing processes. These improvements, though significant, have only kept up with demands for greater schlieren sensitivity as aerodynamicists have begun to study lower and lower flow pressures. In practice today a high sensitivity schlieren system usually requires careful adjustment before and during use to obtain optimum results; this problem has been ignored to some extent because most wind tunnels have enough running time to allow final adjustment to be made with the tunnel in operation.

The U. S. Naval Ordnance Laboratory, Silver Spring, Maryland is at present constructing a wind tunnel capable of Mach 20 with a supply pressure of 4000 atmospheres. The total running time at these conditions is less than two seconds which does not allow time to adjust the system during operation; in addition the tunnel area must be cleared completely of personnel thirty minutes before a run which precludes the presence of an operator and allows the system time to drift mechanically. Obtaining optimum schlieren photographs under these conditions with conventional schlieren techniques would be highly uncertain. Therefore a new approach is necessary for such a wind tunnel.

The most critical adjustment in a high sensitivity schlieren system is the knife edge position. Most of the major sources of system instability can be compensated for by changes in the knife edge position. A logical extension of this fact would be to apply feedback control theory to the system to provide automatic correction for knife edge position error. This approach is therefore proposed as a solution to maintaining schlieren system stability.

THEORETICAL BACKGROUND

The Schlieren System

The fundamental concept upon which any schlieren system functions is that a ray of light passing through a medium in which a gradient of refractive index exists (having a component normal to the ray), will be deviated from its original path. If the undeviated ray is assumed to be along the Z axis, the angular deviations in the XZ and YZ planes are given by

$$\phi_x = \frac{1}{\eta}\int \frac{\partial n}{\partial x}\,dz \qquad \phi_Y = \frac{1}{\eta}\int \frac{\partial n}{\partial Y}\,dz$$

In the case of a wind tunnel test section with two dimensional flow of thickness d (see fig. 1) and constant index medium external to the test section, these equations may be simplified to

$$\phi_x = \frac{d}{\eta_0}\frac{\partial n}{\partial x} \qquad \phi_Y = \frac{d}{\eta_0}\frac{\partial n}{\partial Y}$$

(the equations neglect boundary effects at the windows).

The schlieren method of detecting these deviations in wind tunnels (refer to fig. 2) requires a small but finite light source (the size and shape of this source will be discussed later) and an ideal lens (A) to collimate the source. The light thus collimated is passed

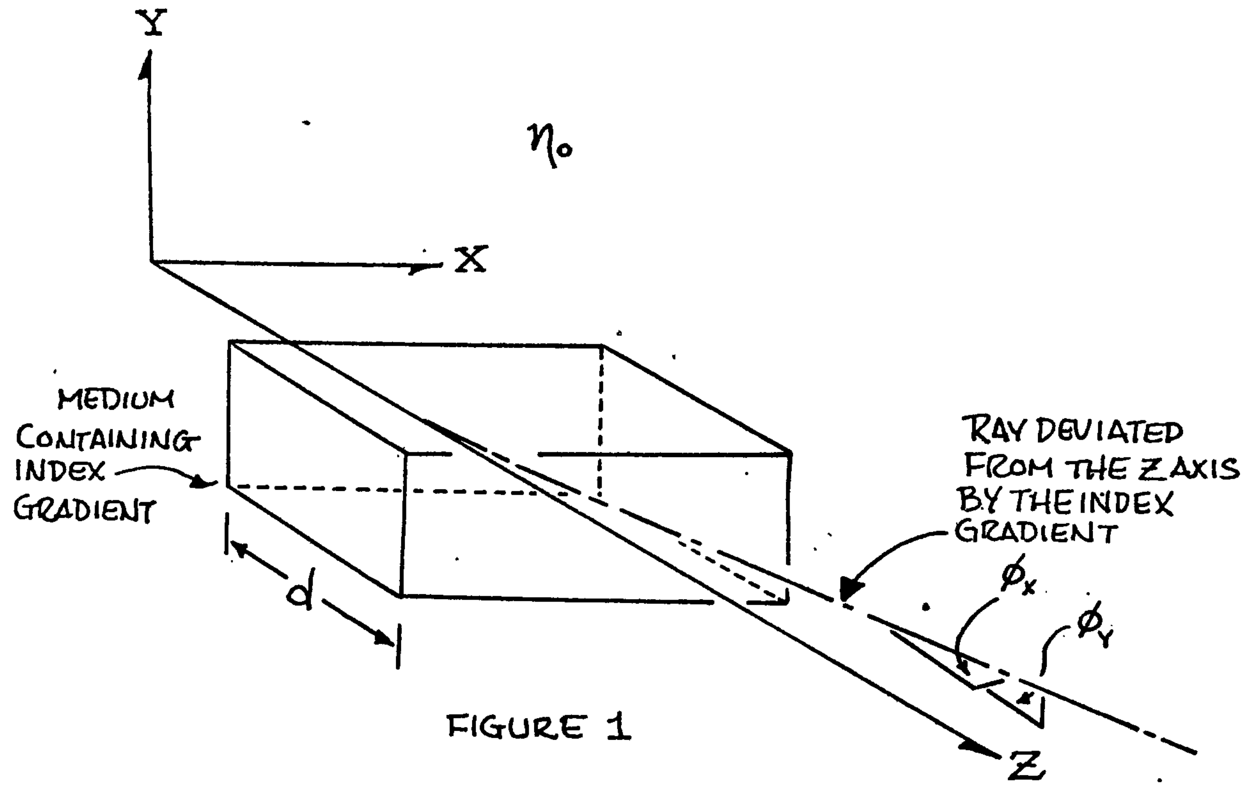

Y
X
η_0
MEDIUM
CONTAINING
INDEX
GRADIENT
d
RAY DEVIATED
FROM THE Z AXIS
BY THE INDEX
GRADIENT
ϕ_x
ϕ_Y
Z

FIGURE 1

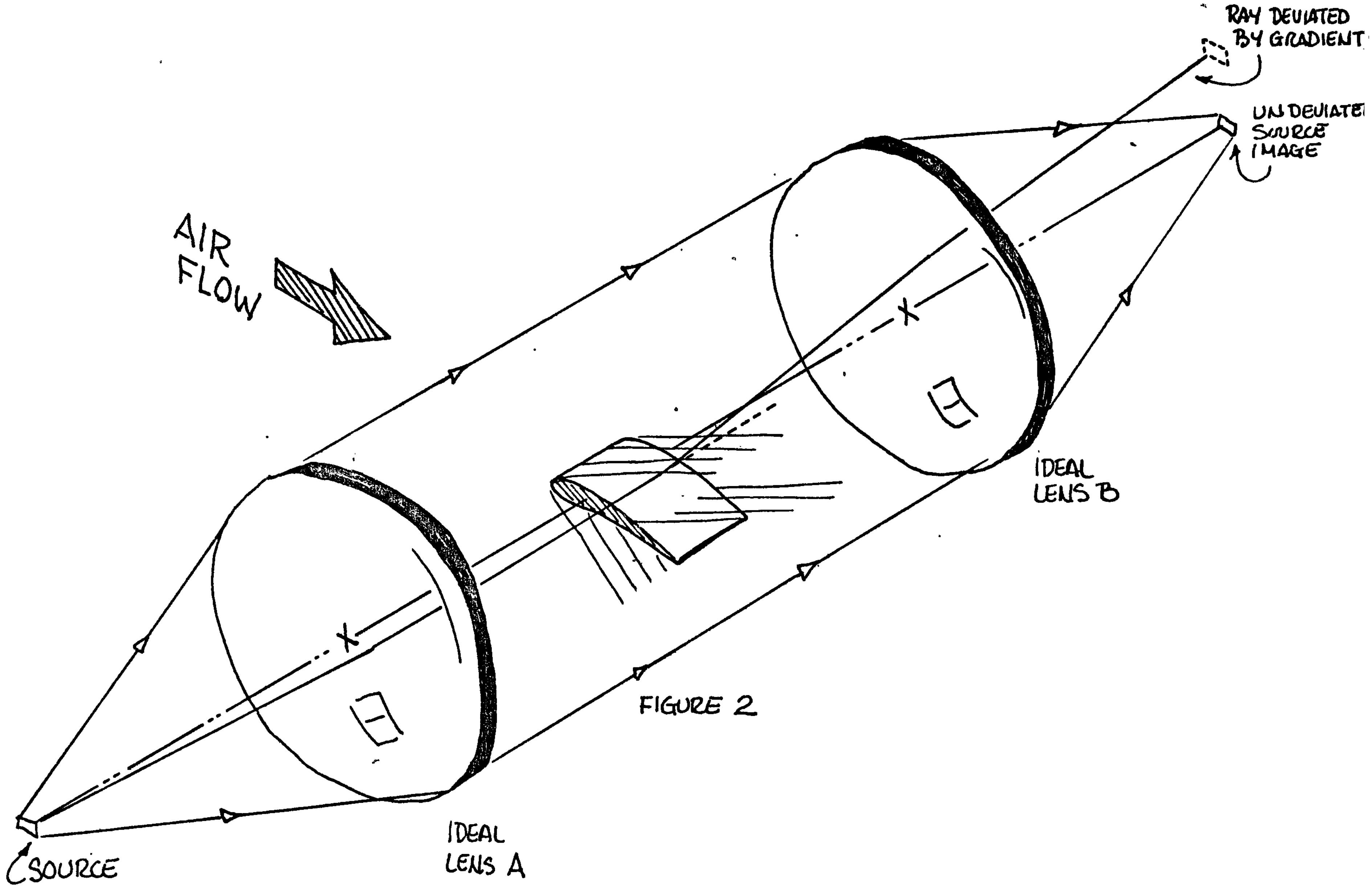

RAY DEVIATED BY GRADIENT
UNDEVIATED SOURCE IMAGE
AIR FLOW
IDEAL LENS B
IDEAL LENS A
SOURCE

FIGURE 2

through the tunnel flow under study. The collimated light is, upon exiting from the flow, refocused by a second ideal lens (B) and an image of the source is formed, but unless the flow contains no index gradients the source image will not be perfect and will exhibit certain aberrations. Since our lenses are ideal the aberrations must be due to the gradients in the flow field.

A close examination of the actual source image will show that it can be described as an infinite number of ideal source images of varying intensity overlapping each other and varying in position about the theoretical focal point of lens (B). A close examination of figure 3 will demonstrate the reason for these aberrations. Lenses A and B and the light source are arranged as described for figure 2, but the wind tunnel flow field is replaced by three identical glass wedges (prisms) which serve as refractive index gradients, wedges 1 and 2 are in the same orientation and wedge 3 is rotated about its optical axis 180°. There are three things to be noted from figure 3: first, the magnitude of the displacement produced by each wedge is the same, because each wedge represents the same gradient and displacement is proportional to gradient; second, the direction of the deflection is in the direction of increased index gradient and third, the deflection angle is independent of position in the schlieren field (wedges 1 and 2 produce

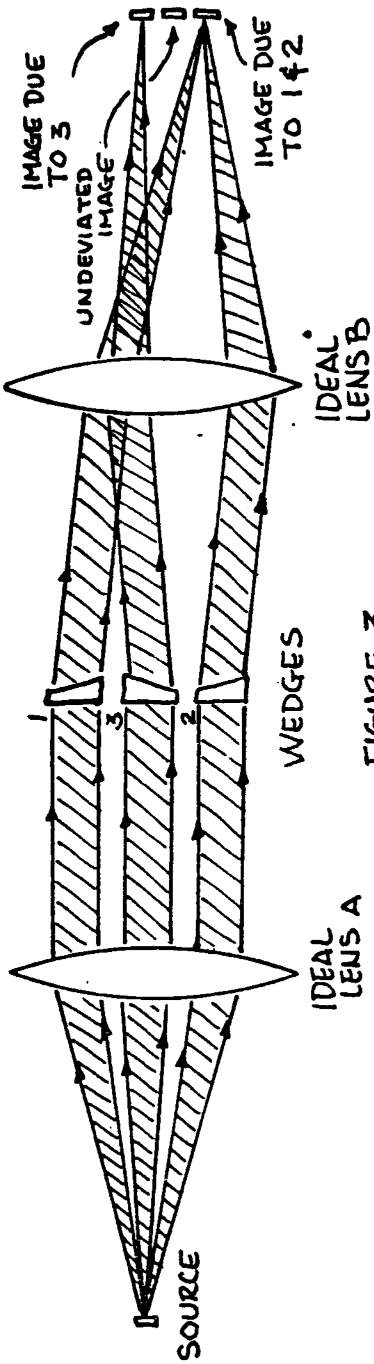

SOURCE
IDEAL LENS A
1
3
2
WEDGES
IDEAL LENS B
UNDEVIATED IMAGE
IMAGE DUE TO 3
IMAGE DUE TO 1 & 2

FIGURE 3

coincident images).

In practice the index gradients of a flow field in a wind tunnel are much more complex than this set of wedges but they produce source image displacements in the same way. Each point in the field produces a deviation of all rays passing through it that is characteristic of the refractive index gradient at that point.

The most common method of making the gradients visible to the eye is the Toepler knife edge method. With this method a simple edge is placed at the focal plane of Lens B so that it obscures some portion (usually half) of the undeviated source image. With this method a gradient causing a deviation away from the edge will appear as an area of greater irradiance than a zero gradient area in the field image. In the same way a gradient which caused a deviation toward the edge will appear as an area of lessened irradiance.

The sensitivity of a schlieren system is usually defined by the minimum angular deviation that the system can detect or record. This minimum detectable angle is simply

$$\Theta_M = \text{Arctan}\,\frac{\Delta d}{f_b}$$

Where d is the minimum shift in source image position which produces a detectable contrast change and f_b is the focal length of lens B. If the physical dimension of the source in the direction of deviation is made small, shifts of its image position are made more detectable. Therefore it is desirable to have sources with at least one small physical dimension. But total flux in the system is proportional to source area. The result is that the most common source shape is a line source or more practically a rectangle with an aspect ratio of 10:1 or more.

A schlieren system parameter related to sensitivity is range. This figure deals with the limits of the system's ability to record the magnitudes of large disturbances. When the system range is exceeded the system is said to be saturated or overdriven. The range of a schlieren system can be extended by increasing the source size which would reduce sensitivity. Special methods exist (such as oolor schlieren) to extend and optimize these somewhat mutually exclusive aspects of the system.

Schlieren System Limitations

As has been shown, a schlieren system provides a method of angular deviation detection, but the system is incapable of distinguishing the source of a deviation. An effective deviation caused by a physical shift (such as vibration or thermal expansion) in some optical component would produce the same image shift at the knife edge as the insertion of an optical wedge into the schlieren field. The magnitude of this problem becomes obvious when one realizes that deviations on the order of 3 or 4 seconds of arc are often required detection levels in schlieren systems. In these high sensitivity systems the range is also very small so that any deviation caused by some undesired optical component shift would cause the system to saturate in the direction of the undesired shift. In addition a situation often arises in the flow in wind tunnel set-ups that produces an overall index gradient (such as the flow over an airfoil) that will drive the schlieren system into saturation and obscure small detail. All of the undesired deviations have one thing in common: they shift the entire flux cone from lens B with respect to the knife edge. They are in effect large positive or negative DC biases superimposed on a small information signal and unless a technique is provided to null out the DC it will saturate the detector. What is needed is a method of moving the knife edge to compensate for any undesired deviations. This is a natural application for feedback control.

Feedback Control

The most obvious feedback control (FBC) system is a human operator examining the schlieren field image and adjusting the knife edge accordingly. This system is often quite practical and has been used almost exclusively for many years. There are drawbacks to this type of FBC:

(1) the compensation rate or response time is slow,

(2) the accuracy and repeatability of response are limited and

(3) the system cannot be considered expendable and therefore should not be exposed to high risk situations.

Yet the human operator is a worthwhile model.

Examining the procedure followed by a human operator as he maintains a schlieren system's alignment we note:

(1) he sees an error in the system alignment,

(2) he turns the knife edge adjustment to correct the error and

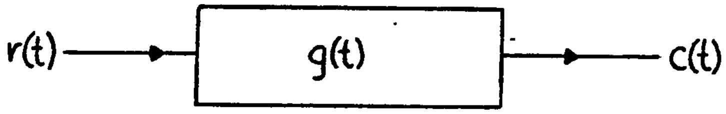
(3) he senses that the correct alignment is reached and stops.

The eyes serve as an optical sensor, the hand and adjustment control become a knife edge positioner and the brain functions as an error-null detector. The human process is in reality much more complex than this and many of its drawbacks are the result of these complexities. The human tries to make detailed value judgments and succeeds in introducing unwanted variability and slow reaction. What is needed is a fast, simple-minded device that looks only at the desired parameter and maintains the value of that parameter constant. The simple linear or proportional FBC system can approach this.

In a schlieren system the necessary components would be a detector to determine actual cutoff adjustment, a reference to indicate desired cutoff, a comparator, an amplifier and a knife edge positioner to make the necessary alignment changes. The detector is used to sense system condition; the detector's output is compared to the reference and the result of the comparison (usually a simple linear subtraction operation) is a signal whose amplitude is proportional to the error in the system condition. The error signal is amplified and used to drive an actuator capable of correcting the system error. Since the error correcting transducer is driven by an amplified error signal the system can never completely correct the error; it can only approach correction in the limit. This leads to the classical design trade-off in all feedback control systems between the contradictory factors: accuracy and stability, for logic would dictate high gain to minimize system error but high gain produces overshoot or in the worst case system oscillation. The design of a FBC system is the optimization of these factors.

Theoretical Development

Linear FBC theory is a branch of linear system theory and its development may begin with a generalized linear system which is described by its transfer function g(t).



The response of g(t) to an input r(t) is the convolution of r(t) and g(t)

$$c(t) = r(t) * g(t) \tag{1}$$

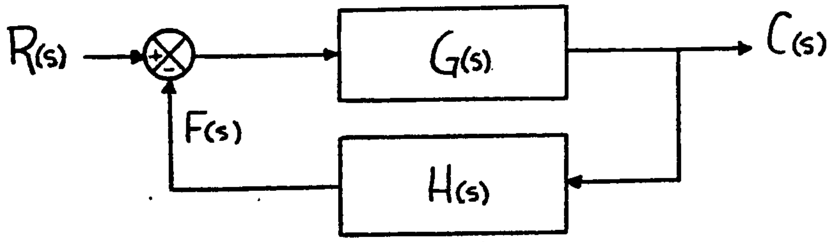
the Laplace transform (1) yields:

$$C(s) = R(s)\,G(s) \tag{2}$$

or

$$G(s) = \frac{C(s)}{R(s)} \tag{3}$$

If a portion of C(s) is feedback to the input of G(s) via a second linear system H(s) two equations may be written:



$$F(s) = C(s)\,H(s) \tag{4}$$

$$\left[R(s) - F(s)\right] G(s) = C(s) \tag{5}$$

substituting 4 into 5 and simplifying:

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 + H(s)G(s)} \tag{6}$$

This equation is fundamental to all FBC and is called the closed-loop transfer function. Normally equation (6) is rational and has constant coefficients. Its roots therefore are either real or conjugate pairs. (6) may then be written:

$$\frac{C(s)}{R(s)} = \frac{K\prod_{j=1}^{\nu}(S+Z_j)}{\prod_{i=1}^{N+2M}(S+P_i)} = \frac{K\prod_{j=1}^{\nu}(S+Z_j)}{\prod_{i=1}^{N}(S+\sigma_i)\prod_{k=1}^{M}\left[S+(\alpha_k+J\omega_k)\right]\left[S+(\alpha_k-J\omega_k)\right]} \tag{7}$$

the system time domain response to $r(t)$=unit step

$$C(t)=\mathcal{L}^{-1}\left[\tfrac{1}{S}(C(s))\right]=\mathcal{L}^{-1}\left\{\frac{K\prod_{j=1}^{P}(S+Z_j)}{S\prod_{i=1}^{N}(S+\sigma_i)\prod_{K=1}^{M}\left[S^2+2\alpha_K S+(\alpha_K^2+\omega_K^2)\right]}\right\} \tag{8}$$

expansion by partial fractions:

$$C(t)=\mathcal{L}^{-1}\left[\frac{1}{S}+\sum_{i=1}^{N}\frac{A_i}{S+\sigma_i}+\sum_{K=1}^{M}\frac{B_K}{S^2+2\alpha_K S+(\alpha_K^2+\omega_K^2)}\right] \tag{9}$$

$$C(t)=\underbrace{1}_{\text{STEADY STATE}}+\underbrace{\sum_{i=1}^{N}A_i e^{-\sigma_i t}+\sum_{K=1}^{M}B_K e^{-\alpha_K t}\sin(\omega_K t)}_{\text{TRANSIENT}} \tag{10}$$

The components of c(t) may be divided into two classes as shown: steady state and transient. The transient component is composed of exponential terms and terms which are products of sinusoids and exponentials. If the values of α and σ are positive the transient response approaches zero as time approaches infinity. Such a system is said to be stable. In reality stability alone is not enough. To guarantee the usefulness of a FBC system the transient terms must become small rapidly; this is necessary to minimize tracking error. The analysis of the transfer function of a FBC system in terms of its transient and steady state response in the time and complex frequency domain is the approach generally used to design and evaluate such systems. By balancing the functional requirements of the system against inherent physical limitations, a practical system design is obtained.

OBJECTIVE

The primary objective of this investigation was to determine the practical feasibility of using feedback control in the stabilization of high sensitivity schlieren systems. The approach used was to design a simple FBC system and evaluate its performance in a schlieren system.

SYSTEM DESIGN

The design of the feedback control system, due to practical limitations on available materials, proceeded on a somewhat less than ideal path of development. The knife edge positioner for example had to be evolved from an initial concept using an audio loudspeaker through several intervening steps to the final device. The original mathematical model for the system changed as each component of the system was implemented. A change in the model was necessary because each component included physical limits and characteristics not included in the assumptions of the original model. Some of these eccentricities were non-linear in nature and proved to be difficult at best to treat mathematically. As an example the cadmium sulfide (CdS) detectors used in the knife edge position sensor have a "memory". this is, their response is affected by their previous history of exposure to light. To minimize this problem the cells used in the sensor were matched and before each use they were both exposed to a 100 watt bulb at 12 inches for several seconds. This in effect "erased" differences between the cells.

The system design was in reality a parallel development of all its components and no component was developed independently of the others, but to simplify the presentation these major components will be treated separately:

(1) the cutoff sensor and reference,

(2) knife edge positioner and

(3) comparator amplifier.

The Cutoff Sensor and Reference

The position of the knife edge is usually treated in terms of % cutoff:

$$\% \text{ CUTOFF} = \frac{I_i - I_o}{I_i} \times 100$$

Where I_i is the total flux reaching the knife edge plane and I_o is the portion of I_i which passes over the knife edge. This is illustrated in figure 4.

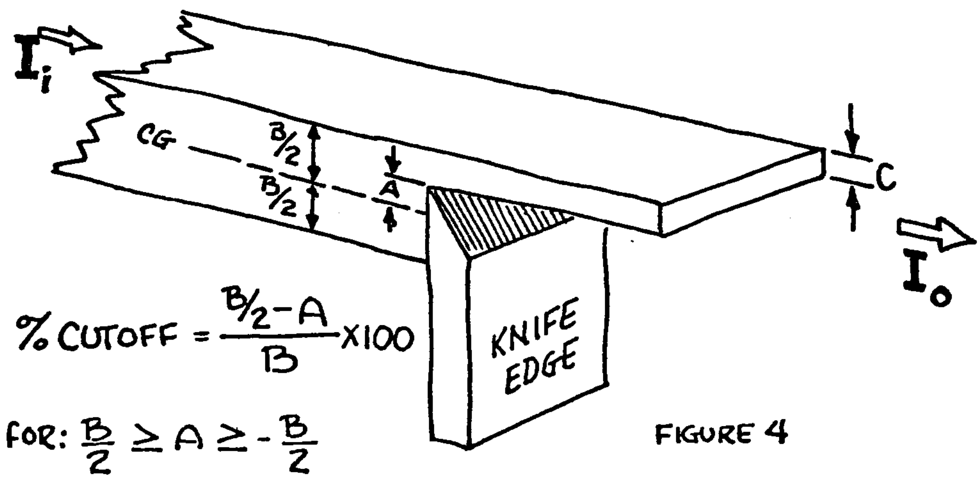


FIGURE 4

Figure 4 shows that the cutoff is a function of the position of the knife edge with respect to reference defined by the "center of gravity" of flux cone at the knife edge. Thus the cutoff sensor must detect the relative position of the knife edge with respect to this cone and not an absolute mechanical position. Since the cone may shift position, shape or intensity and only position shifts are to be detected, a differential detector is desirable. The method chosen was a bridge null device. A portion (approximately 4%) of the total flux cone was stripped off by a beam splitter, attenuated by an amount equal to desired cutoff and directed to a CdS photoresistive cell. This cell produced the reference signal. A portion of flux (approximately 4%) which was not obscured by the knife edge was also directed to a CdS cell to produce the knife position signal. When the knife edge was positioned to produce desired cutoff the outputs of the two CdS cells balanced to produce a zero error condition independent of the absolute value of I_i. Figure 5 shows the optical layout. The beam splitters are pieces of 2" x 2" slide cover glass. The positions of the two cells are such that they are at similar points in the diverging flux cone.

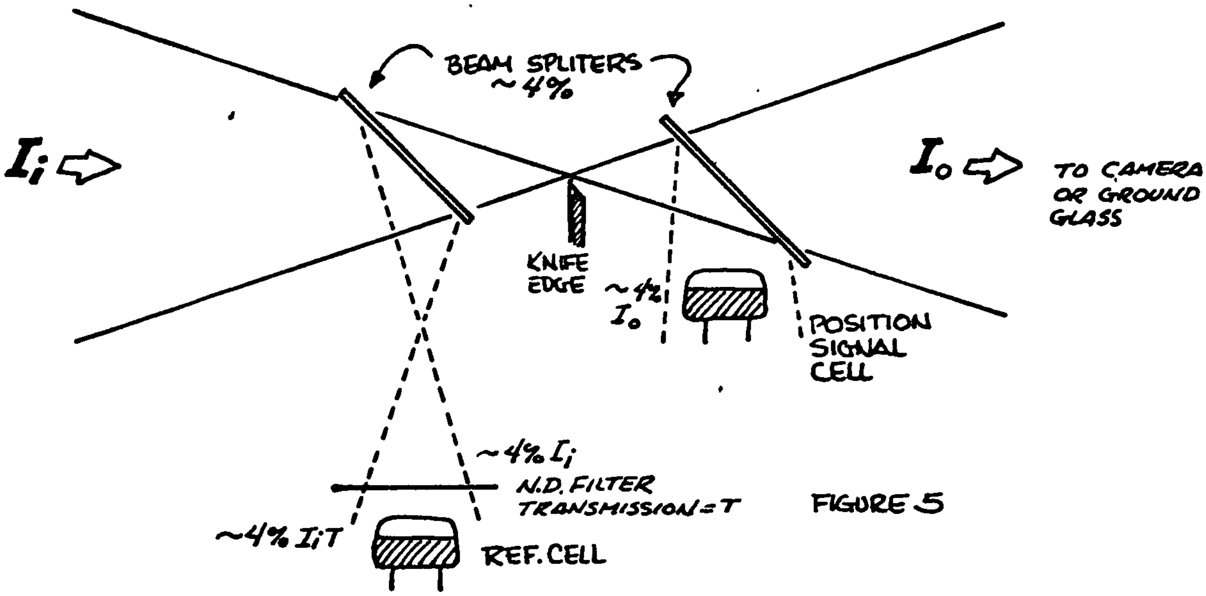


FIGURE 5

The Knife Edge Positioner

Initially the positioner was envisioned as a light-weight razor blade mounted on a loudspeaker voice coil. This approach had several problems:

(1) speakers are, in general, not critically damped,

(2) speakers with enough linear travel to be useful are resonant at frequencies low enough to produce instability and

(3) the cone is an integral part of suspension and provides damping and restoring force to the voice coil.

Any modification (partial or complete removal) of the cone to simplify optical geometry disturbed the mechanical characteristics of the voice coil.

The final design chosen is shown schematically in figure 6

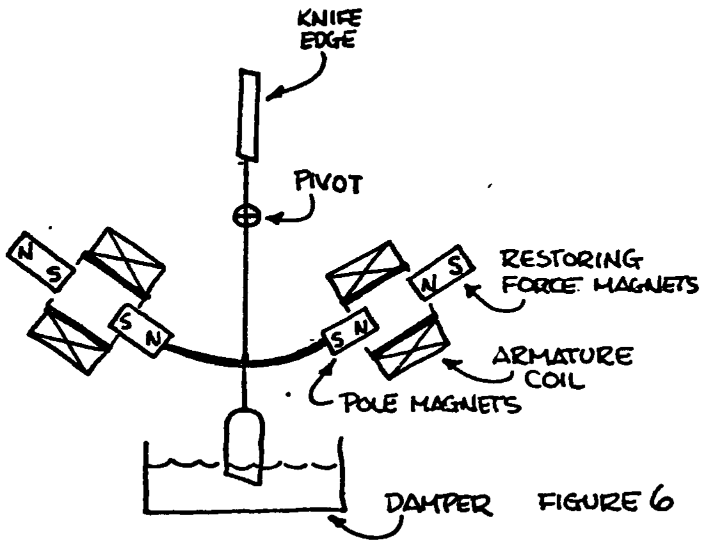


FIGURE 6

The knife edge (aluminum foil) is mounted on a pendulum made of light weight wood with a cross bar. On the cross bar are two small pieces of ferrite magnet. These movable magnets form the positioner armature poles and are mounted within two fixed coils phased to deflect the pendulum in proportion to the current flowing in them. Restoring force is provided by two adjustable permanent magnets that repel the armature magnets. In addition, attached to the pendulum is a small plastic blade which extends into a cup below the pendulum. By varying the amount and composition of liquid in the cup, damping can be adjusted. See figure 7.

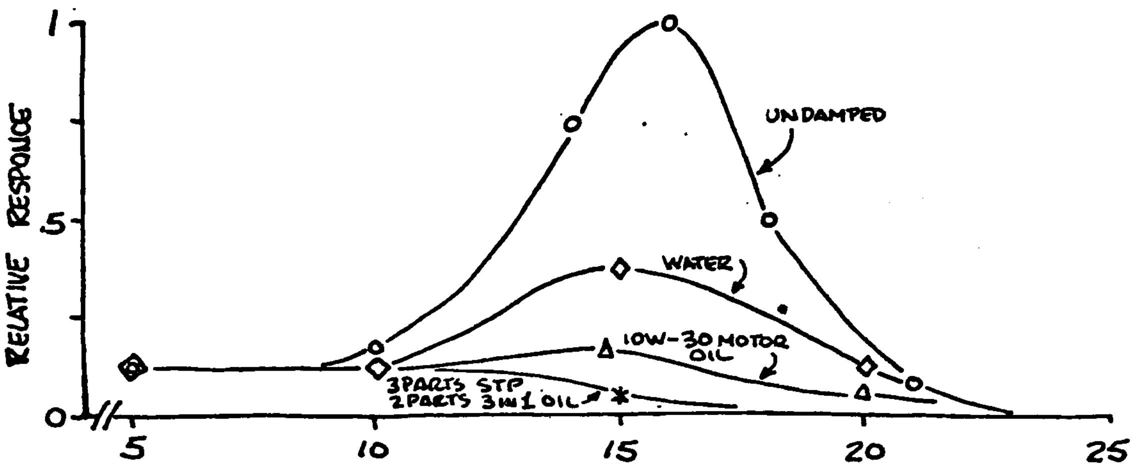


FIGURE 7

This positioner although somewhat crude in construction was in many ways ideal since restoring force (therefore resonance) and damping were adjustable.

The Comparator Amplifier

The knife edge positioner drive requirements are relatively high, ~.6 amperes across approximately 20 . The design of a trouble-free linear DC amplifier with the necessary 6-10 watt output is an involved design exercise in itself. To circumvent this, a pulse width modulated (PWM) amplifier design was used. In this approach the amplifier is merely a high power switching circuit and its linearity is unimportant.

The PWM amplifier requires an unusual type of input. Instead of the usual voltage amplitude analog, the PWM amplifies pulses of fixed amplitude with widths proportional to signal amplitude. If the pulse rate is much higher ($f_p > 2 f_r$) than the necessary signal frequency response, then the average value of the output voltage or current within the signal frequency response range of the amplifier will be proportional to input. This is shown in figure 8.

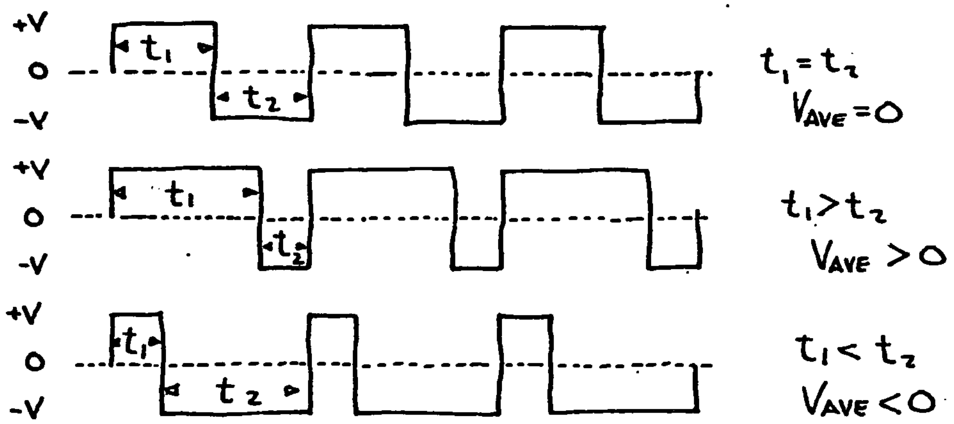


FIGURE 8

The circuit necessary to compare the response of the two CdS cells and produce an output to drive the PWM amplifier proved to be quite simple. An astable multivibrator (AMV) modified as shown in figure 9A was ideal for this purpose.

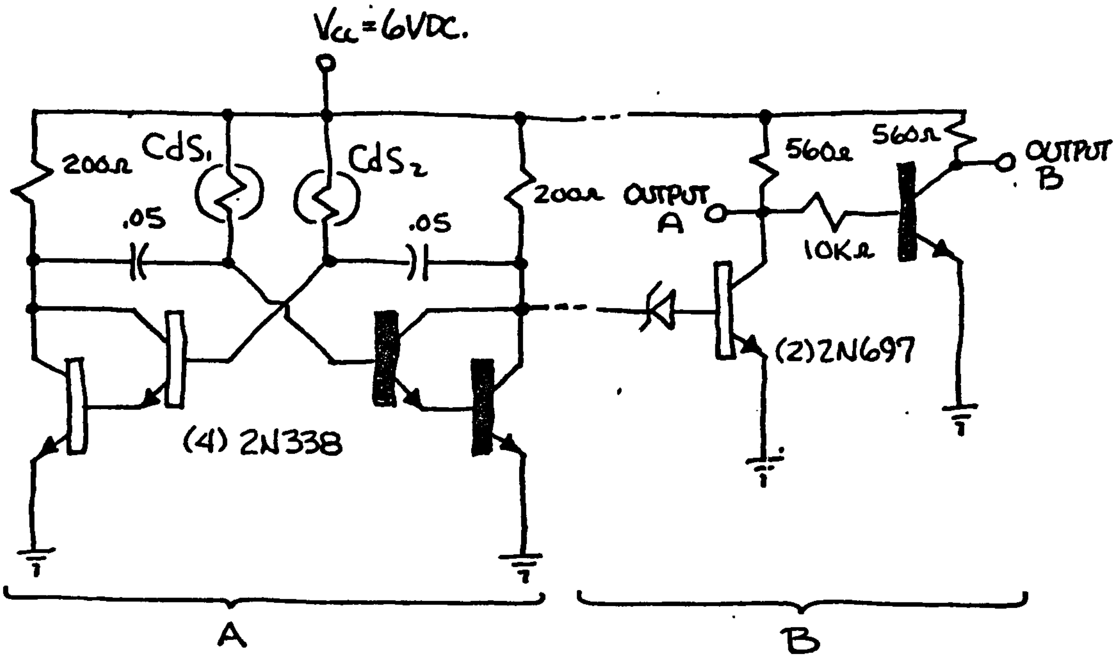


FIGURE 9

From the basic design development of this type of multivibrator it can be shown that the circuit will oscillate for all values of R (the CdS cell resistance) between:

$$\beta R_c \geq R \geq 5.8 R_c$$

where β is the transistor common emitter current gain. And R_c is the collector resistance. For the AMV to oscillate over a large portion of the range of the CdS cells (see figure 10) it was then necessary to make β large. The Darlington connection of two transistors produces a composite $\beta = \beta_1 + \beta_2 + \beta_1 \beta_2$. For the transistors used (β=75) the composite β_c=5800 resulting in a 1:1000 range for the multivibrator.

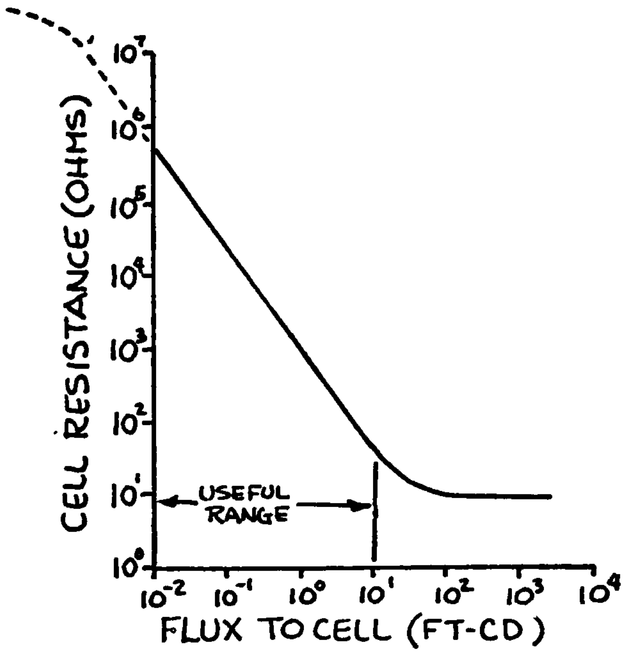


FIGURE 10

The period of each half cycle of the AMV is approximately equal to RC thus the resistance of each CdS cell and its associated capacitor control the length one half of the square wave. If the capacitors are equal the average value of the wave form is zero when the CdS cells receive equal light. The circuitry shown in figure 9B is a buffer to prevent the AMV comparator from being affected by amplifier loading.

The amplifier as stated earlier is a switching circuit, that is, it consists entirely of transistors which are operated between their saturation and cutoff states. The final circuit used is shown in figure 11.

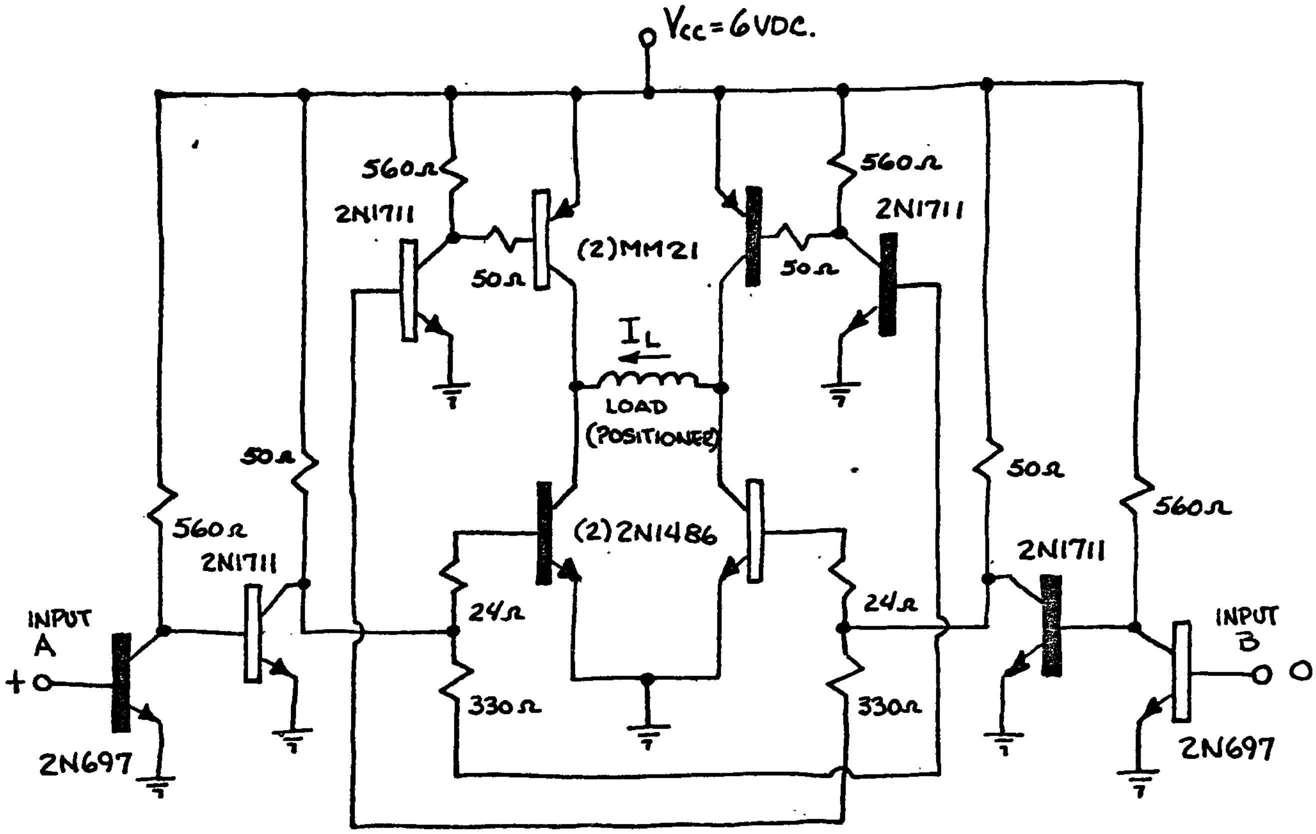
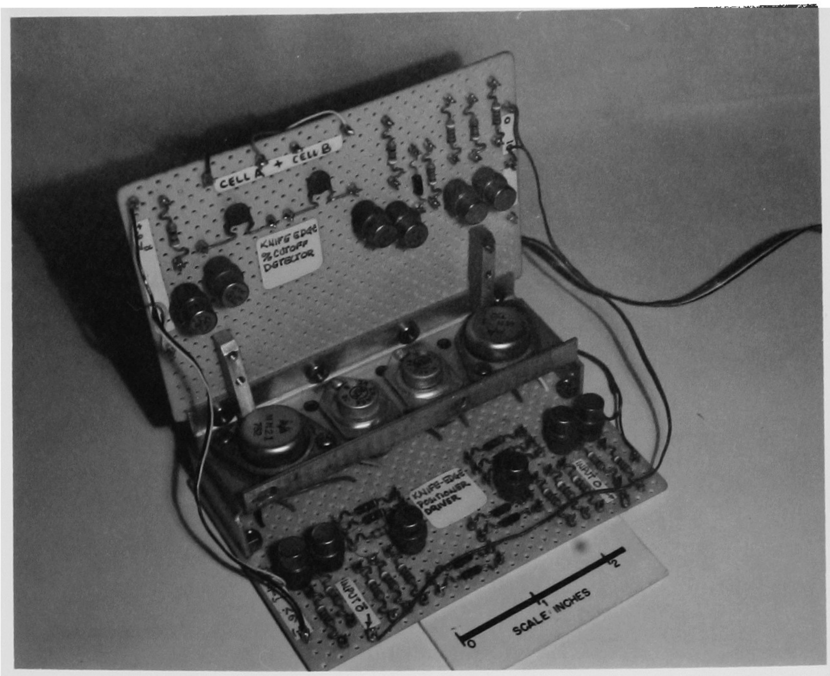


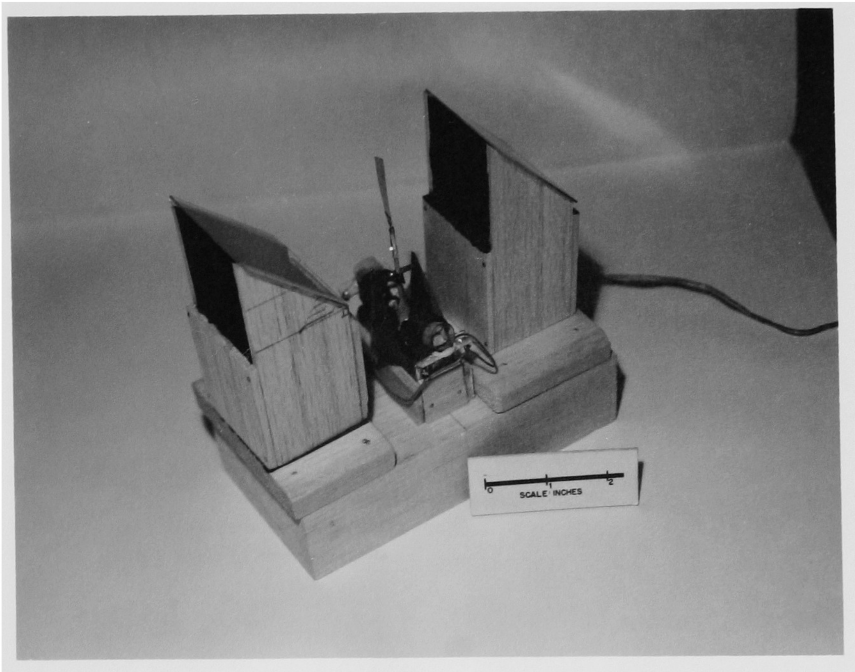
FIGURE 11

To demonstrate the circuit's function, the amplifier is shown with input (A) positive and (B) zero (only one input can be positive at any time due to the comparator buffer design). The saturated transistors are shown in black, the cutoff transistors in white; the conventional current flow in the load is shown for this input configuration. Note that due to symmetry the reversing of inputs would reverse the current flow through the load. In reality inputs A and B are being reversed several hundred to several thousand times a second so that there is an alternating current flow in the load. In addition a DC component (due to the asymmetrical waveform from the comparator) exist if the flux reaching the CdS cells is not equal; this DC component produces motion of the positioner.

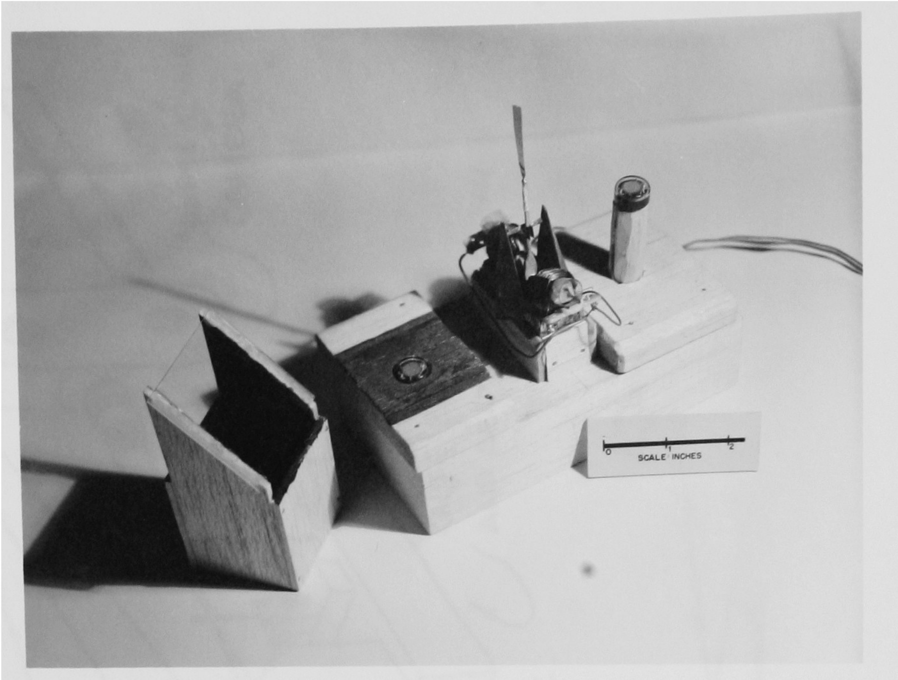
The assembled form of FBC system components is shown in the following photographs (figures 12-15) and the positions of each in the schlieren system is shown in figure 16.



DETECTOR AND KNIFE EDGE DRIVER ELECTRONICS
FIGURE 12

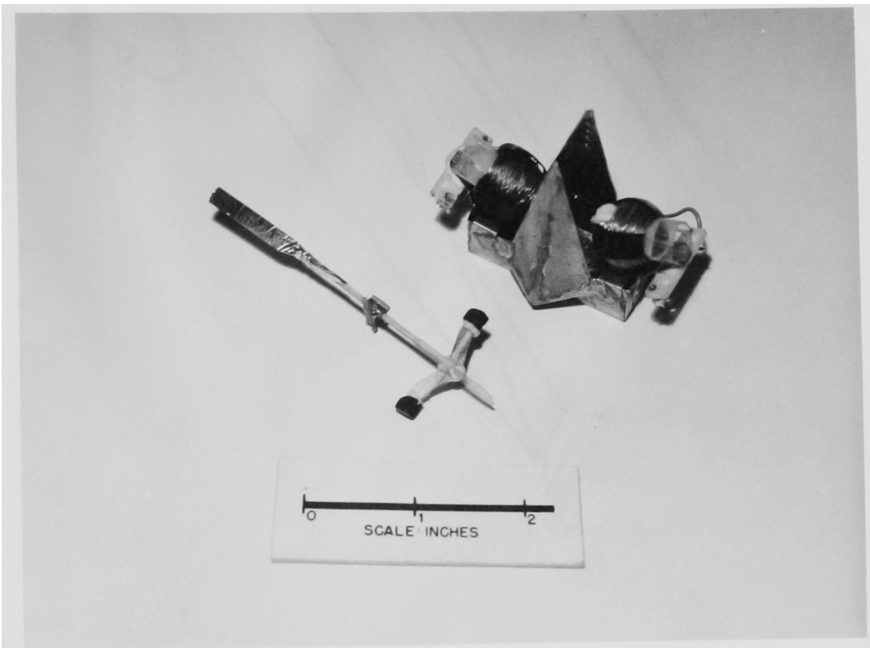


KNIFE EDGE POSITIONER AND BEAMSPLITTERS
FIGURE 13



BEAMSPLITTERS REMOVED TO SHOW CdS CELLS

FIGURE 14



POSITIONER DISASSEMBLED

FIGURE 15

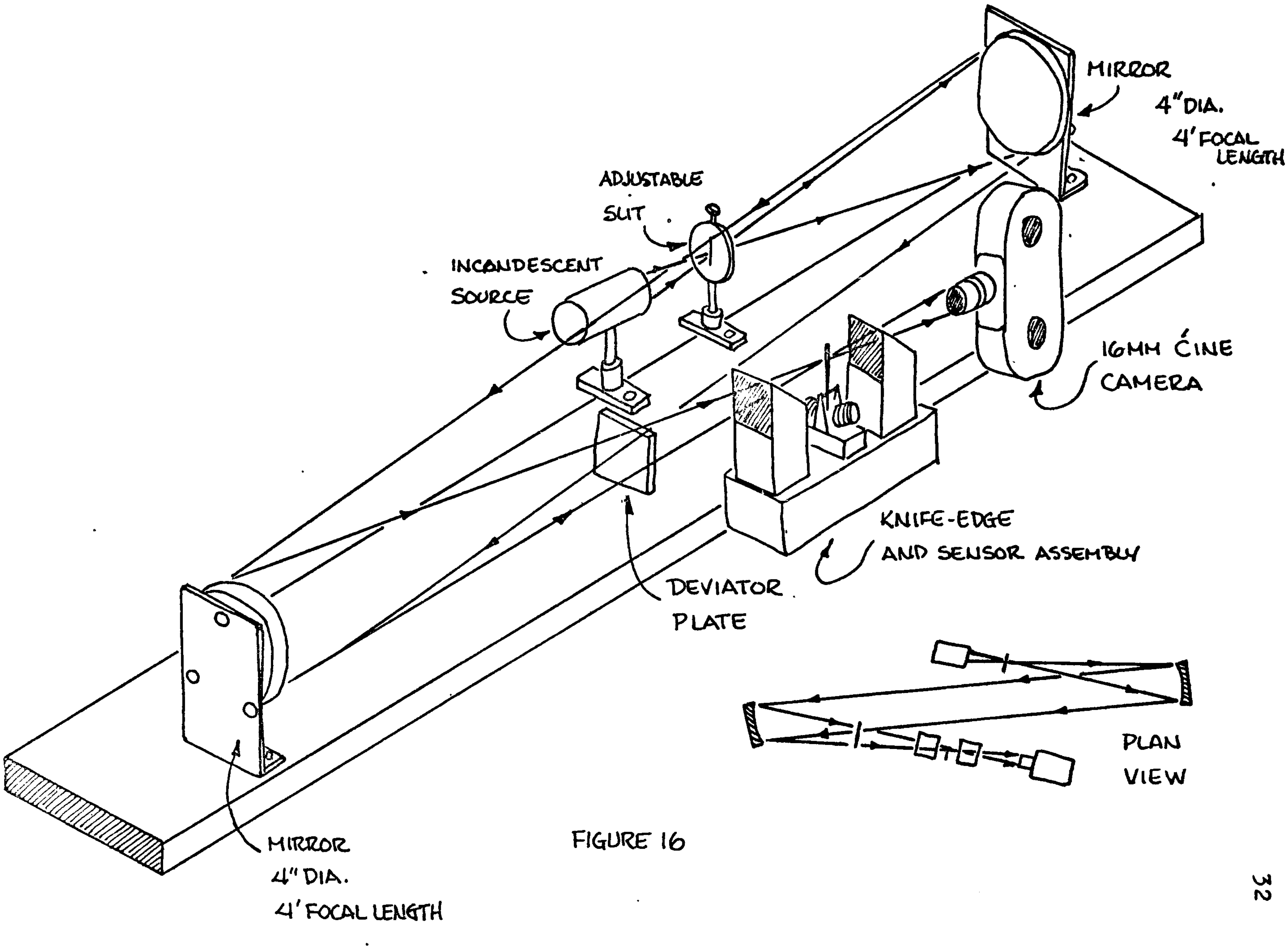

MIRROR
4"DIA.
4' FOCAL LENGTH
ADJUSTABLE
SLIT
INCANDESCENT
SOURCE
16MM ĆINE
CAMERA
KNIFE-EDGE
AND SENSOR ASSEMBLY
DEVIATOR
PLATE
PLAN
VIEW
MIRROR
4"DIA.
4' FOCAL LENGTH

FIGURE 16

EXPERIMENT DESIGN

To evaluate the feedback control stabilization concept a schlieren system was assembled. The overall layout is shown in figure 16. The sensitivity of this schlieren system, operated with a .005 inch source size, was about 4 seconds of arc. In addition to the usual schlieren system components there was a glass plate, .025 inches thick, mounted on a calibrated pivot which allowed it to rotate in the optical path of the converging flux cone to the knife edge. This plate allowed the cone to be deviated by accurately calibrated amounts with respect to the knife edge. Using this deviator plate it was possible to introduce controlled disturbances in the stabilized schlieren system alignment. By recording the response to these disturbances in the form of density variations on 16mm motion picture film, it was possible to obtain stability data about the system. This was done both with the FBC system operative and inoperative. The comparison of these two conditions for each type of disturbance provided an indicator of system stability improvement.

Two types of disturbance were used in the evaluation procedure:

(1) continuous sinusoidal disturbance at several frequencies

and

(2) step function changes in system alignment.

(These were chosen because they conform to general practice in feedback control evaluation.)

Both of these were generated by moving the glass deviator plate manually; for the sinusoidal disturbances the ticking of a watch (four ticks per second) was used to synchronize the disturbance frequencies (0.5 Hz, 1 Hz, 2 Hz and 4 Hz) and for the step disturbance the deviator was shifted abruptly from an initial position to a position against an adjustable stop. Before actually recording data these manual operations were practiced while observing an oscilloscope until each could be reproduced reliably.

Additionally the FBC system was evaluated with two schlieren source widths (.005 inches and .010 inches). The schlieren source size affects both the schlieren system's sensitivity to a disturbance and the FBC system's ability to correct the disturbance. In all cases the dependent variable was flux out of the schlieren system; this was recorded with respect to time as density with a 16mm motion picture camera operating at ten pictures per second. The two experiments are shown diagrammatically in figure 17.

SINUSOIDAL DISTURBANCE EXPERIMENT

	SCHLIEREN SYSTEM SOURCE SIZE .005 INCH		SCHLIEREN SYSTEM SOURCE SIZE .010 INCH	
	FBC SYSTEM ON	FBC SYSTEM OFF	FBC SYSTEM ON	FBC SYSTEM OFF
0.5 Hz ±0.006 INCH DEVIATION	DATA Response variable, flux variation recorded as density variation			
1.0 Hz ±0.006 INCH DEVIATION				
2.0 Hz ±0.006 INCH DEVIATION				
4.0 Hz ±0.003 INCH DEVIATION				

STEP INPUT DISTURBANCE EXPERIMENT

	SCHLIEREN SYSTEM SOURCE SIZE .005 INCH		SCHLIEREN SYSTEM SOURCE SIZE .010 INCH	
	FBC SYSTEM ON	FBC SYSTEM OFF	FBC SYSTEM ON	FBC SYSTEM OFF
+0.005 INCH STEP	DATA Response variable, flux variation recorded as density variation			
+0.010 INCH STEP				
-0.005 INCH STEP				
-0.010 INCH STEP				

FIGURE 17

EXPERIMENTAL PROCEDURE

After the feedback controlled schlieren system was assembled, alignment and calibration were necessary. The schlieren alignment was conventional; the incandescent light source filament was imaged on an adjustable slit, set to specified size with a calibrated optical comparator. The light passing through the slit was collimated by the first parabolic mirror and directed to the second mirror, the second mirror directed the light through the deviator and imaged the slit on the knife edge. Once this was accomplished the FBC system was calibrated. First, with the FBC system off and the deviator set at zero, the knife edge was positioned to 50% cutoff using a Gamma Scientific photometer. The FBC system was then turned on and again the cutoff was set at 50% by nulling the comparator. This procedure set up the system. Once set up any change in the system could be noted by monitoring the knife edge positioner current.

To examine the steady-state response of the overall system data were taken of % cutoff as a function of image deviation for .005, .010 and .025 inch source size. The resulting curves are shown in figures 18-20.

Once this initial evaluation was accomplished, the

CLOSED LOOP D.C. RESPONCE OF THE FEEDBACK CONTROL SYSTEM WITH SOURCE SIZES OF .005,.010 AND .025 INCHES

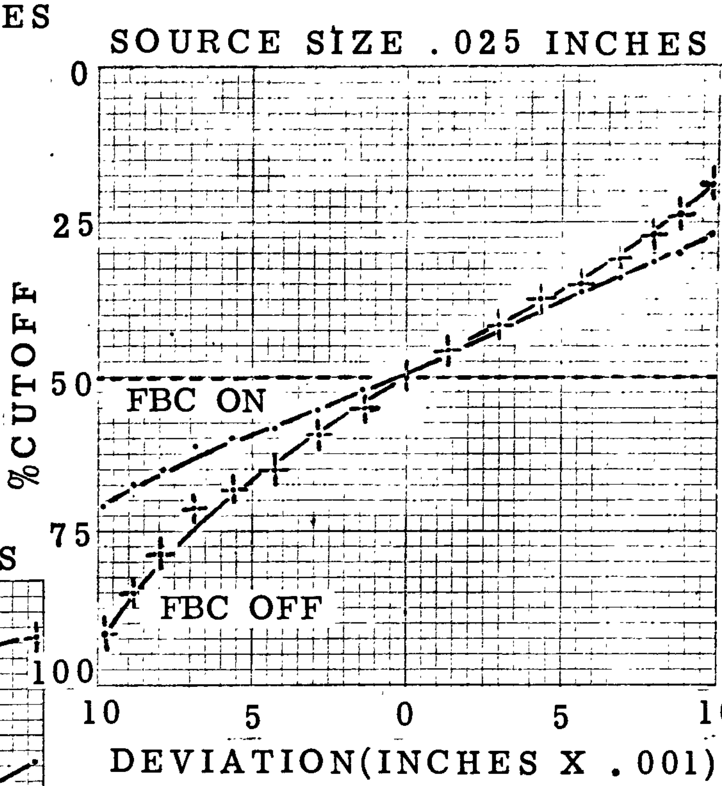


FIGURE 18

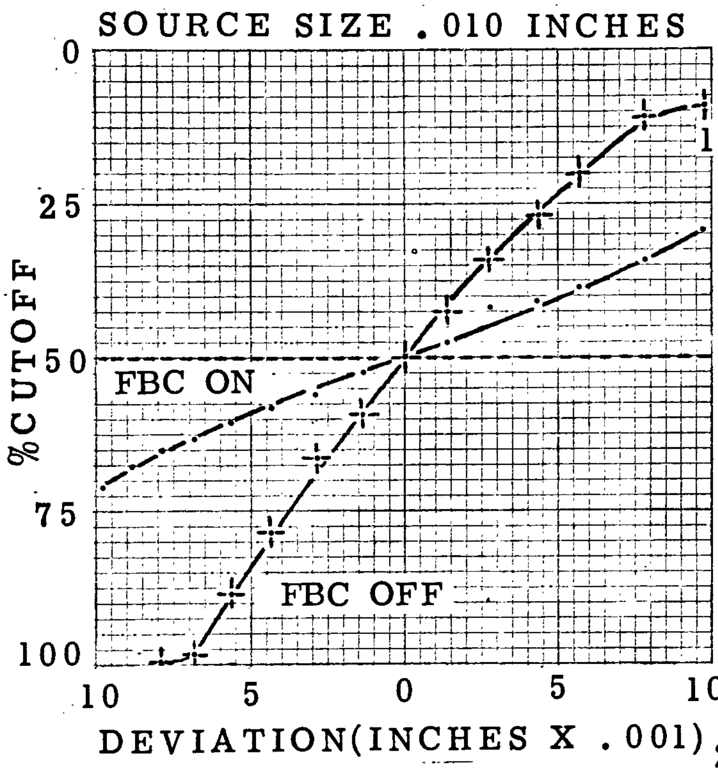


FIGURE 19

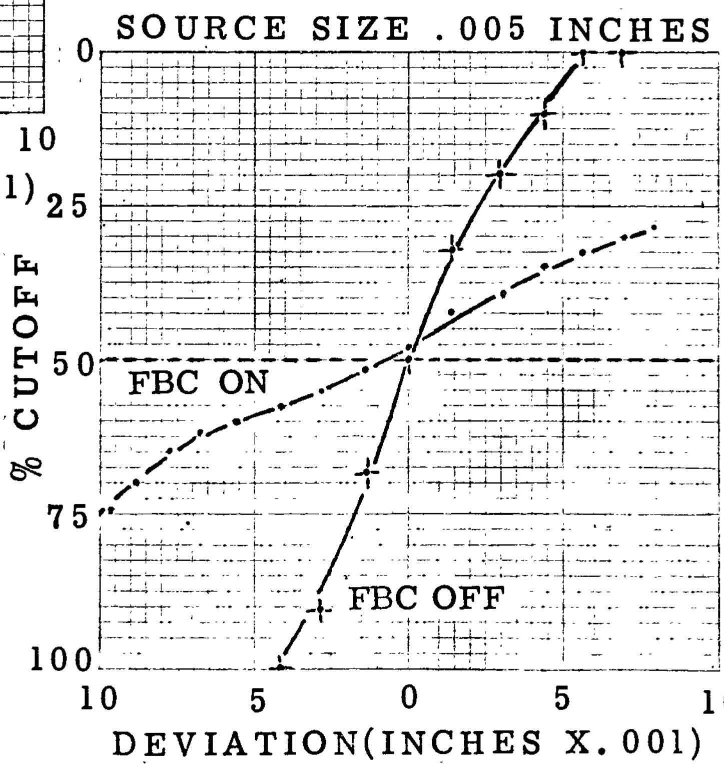


FIGURE 20

system was aligned and calibrated and the experimental series described in the Experiment Design was carried out. The 16mm motion picture camera with its lens removed was placed in the diverging beam from the knife edge. The Gamma Scientific photometer was used to determine a neutral density filter value to reduce the output flux to a value compatible with the sensitivity of the Plus-X film used. With the camera operating, each of the experimental variable combinations was carried out, after each experimental run the calibration was checked.

RESULTS

Sinusoidal Disturbance Experiment

The curves shown in figures 21-28 are plots of the results of the sinusoidal disturbance experiment. Curves of data taken with the system off are marked with (+) and with the system on are marked with (.); the vertical axis in all cases is recorded film density and the horizontal axis is time. It should be noted that due to the nonlinear nature of density there is compression in the direction of increased density. This is because the change in density between 50% cutoff and 0% cutoff is approximately .3 or .35, while the change in density between 50% and 100% is about 1.4-1.7.

In each case the density variation caused by the deviator is significantly reduced when the FBC system is operating. Response of this particular system was decreased somewhat at 4 Hz; this should not be considered a physical limit, the limitation is due to the response of the knife edge positioner. (Note: in the curves showing the 4 Hz disturbance there is an overall envelope in each case at approximately 1 Hz; this is due to a marginally sufficient sampling rate of 10 samples per second.)

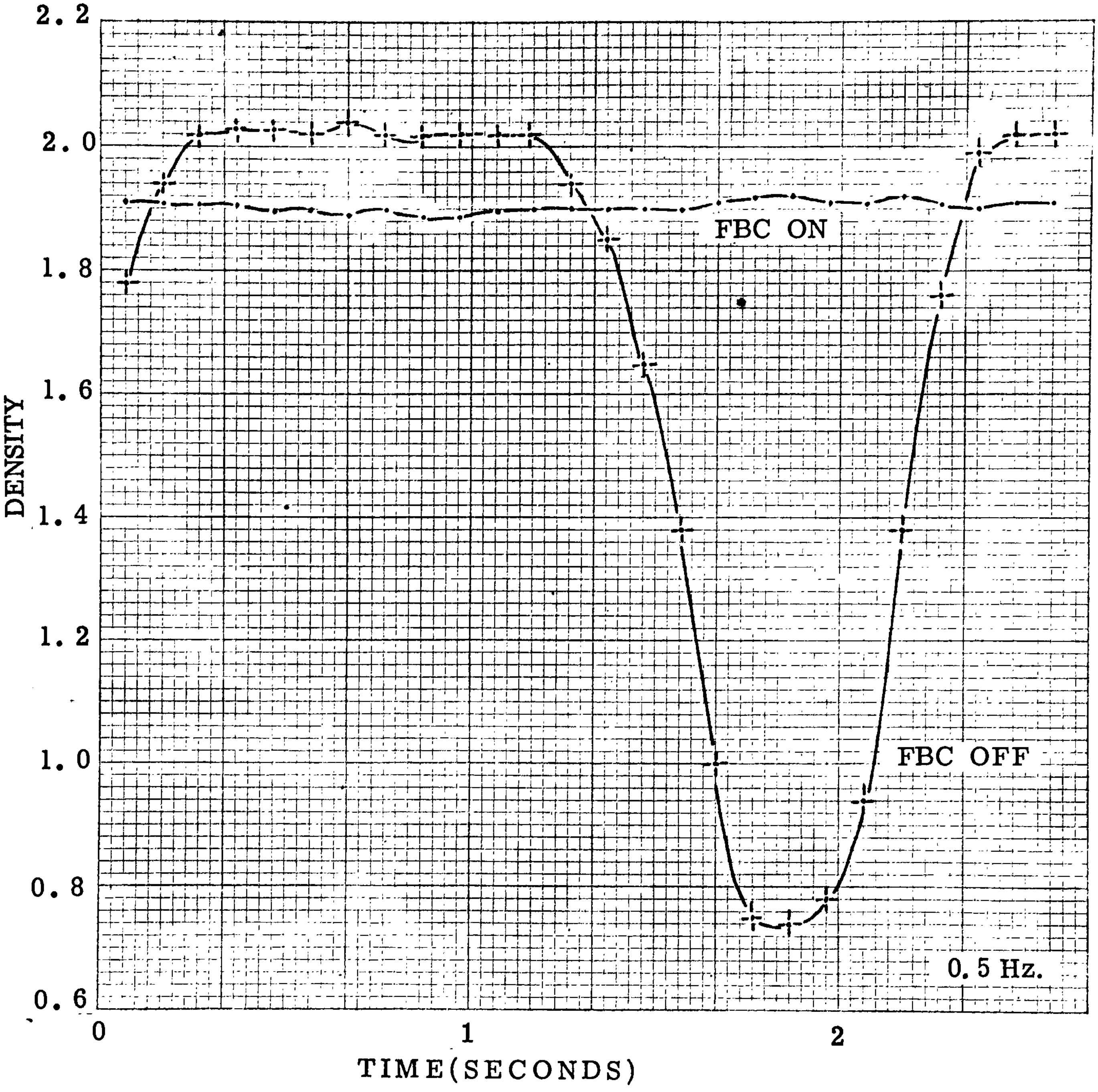


FIGURE 21

SINUSOIDAL DISTURBANCE .005 INCH SOURCE SIZE

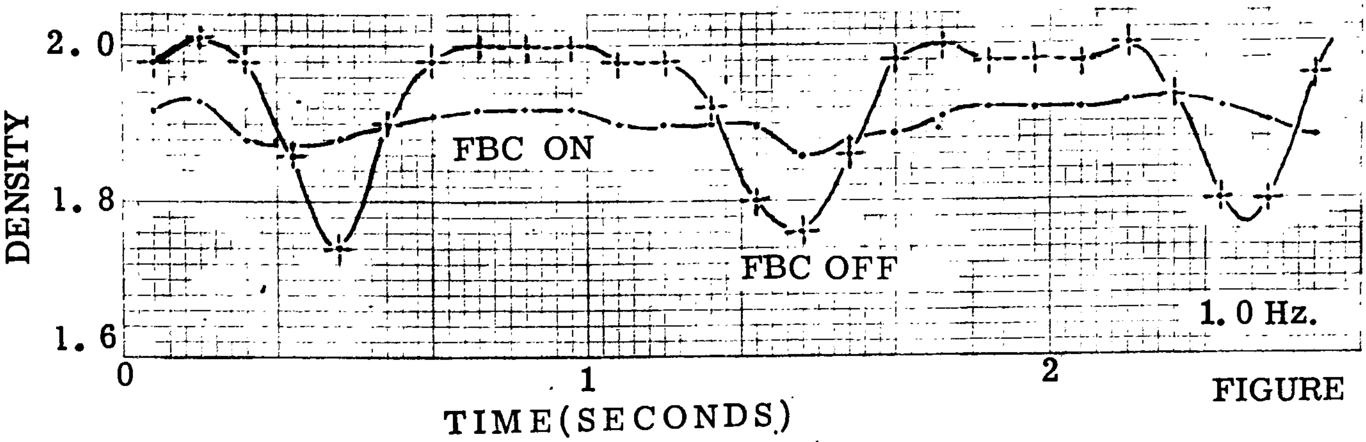


FIGURE 22

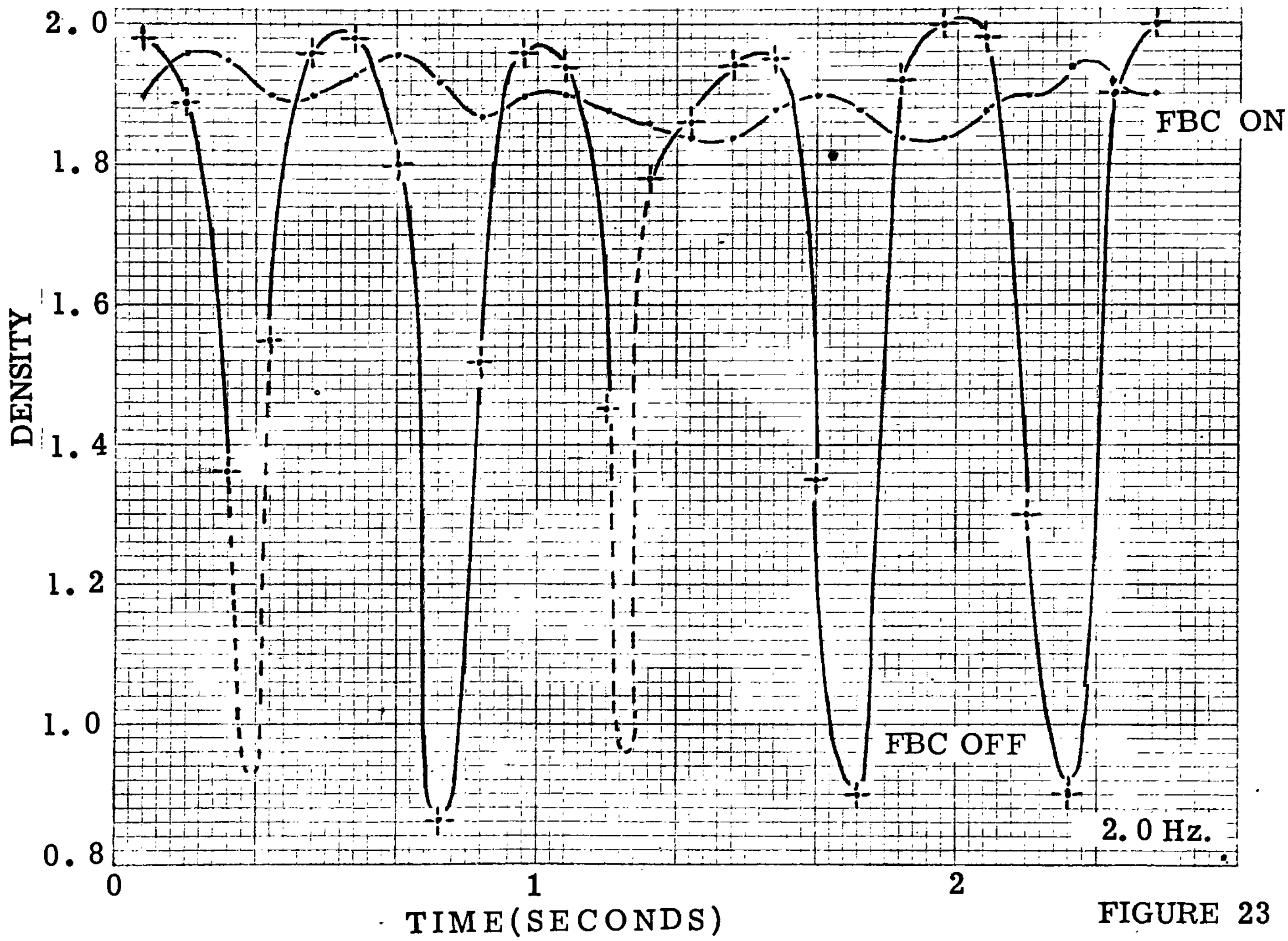


FIGURE 23

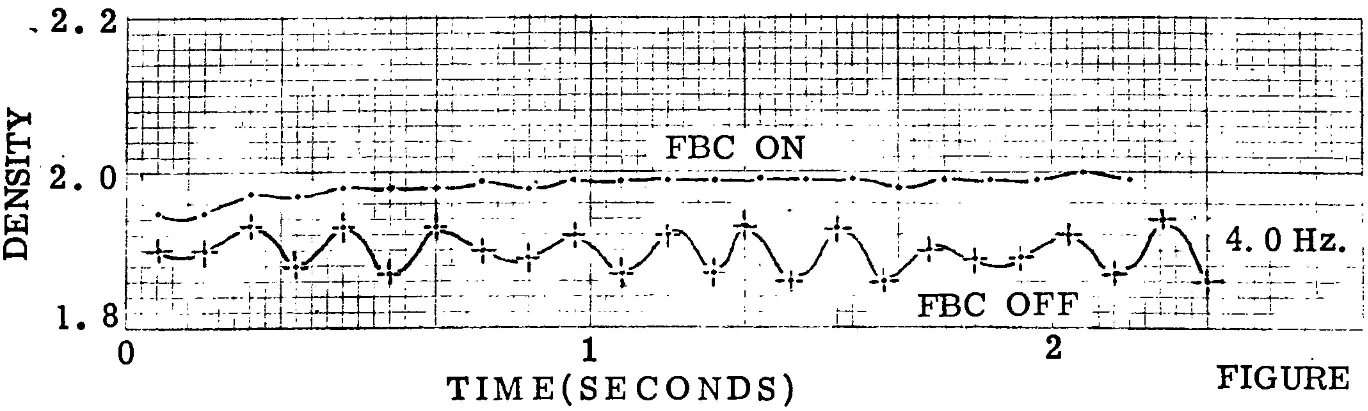


FIGURE 24

SINUSOIDAL DISTURBANCE .005 INCH SOURCE SIZE

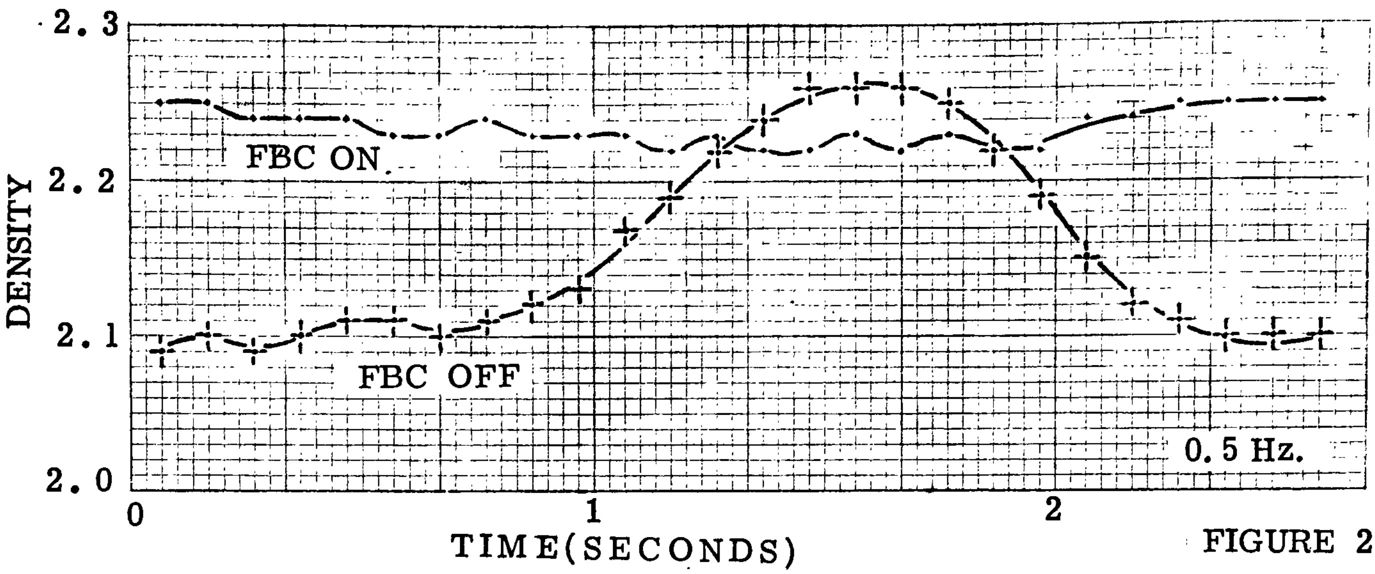


FIGURE 25

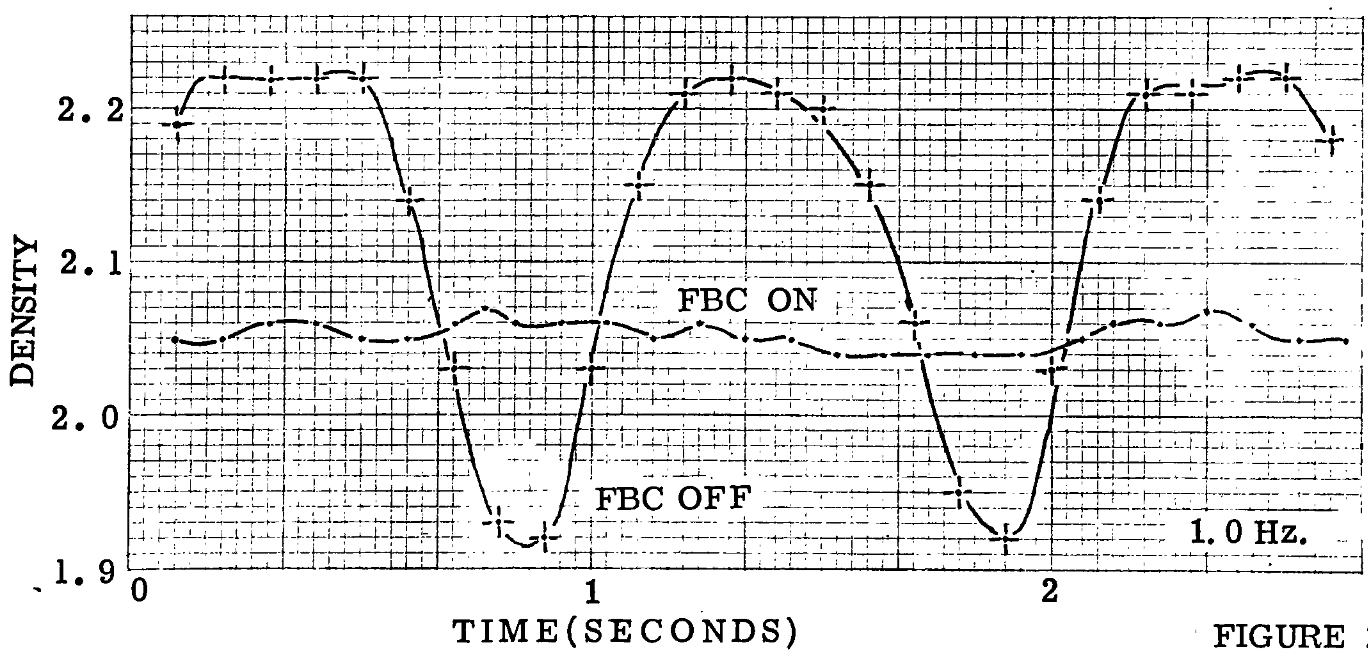


FIGURE 26

SINUSOIDAL DISTURBANCE .010 INCH SOURCE SIZE

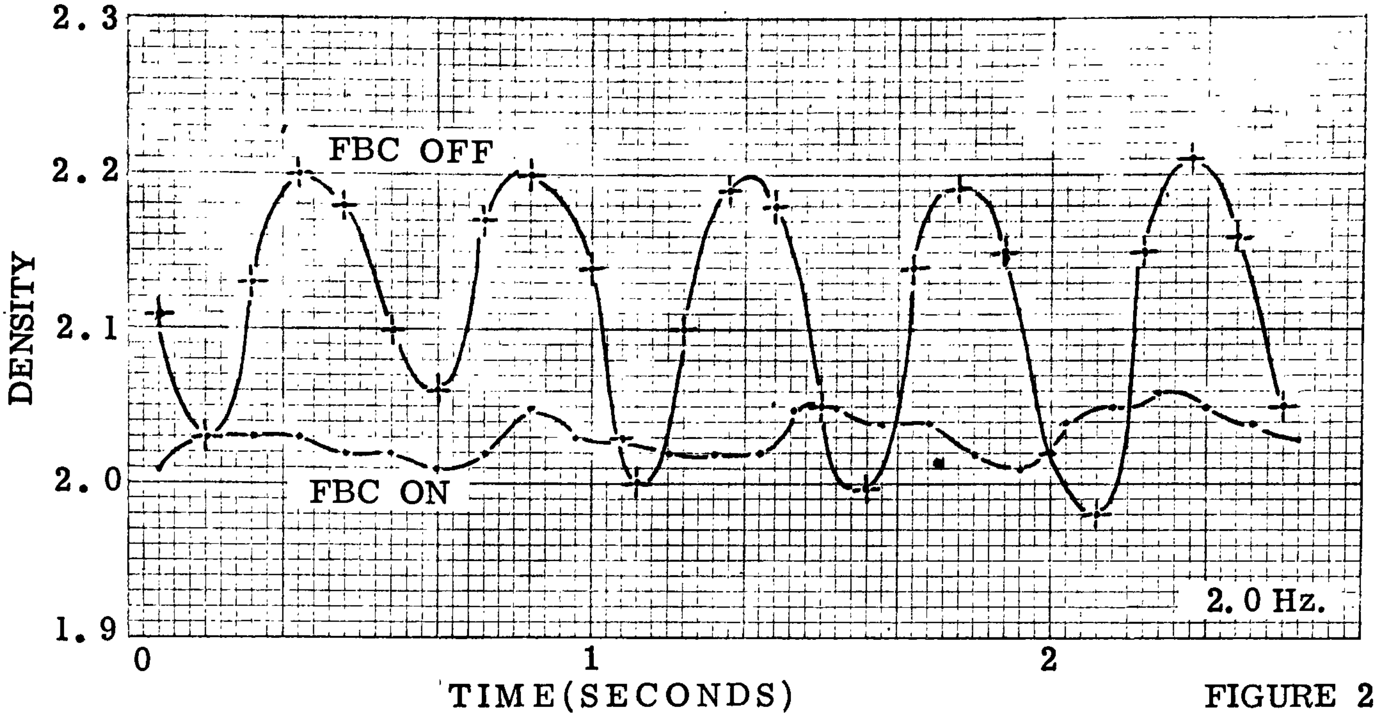


FIGURE 27

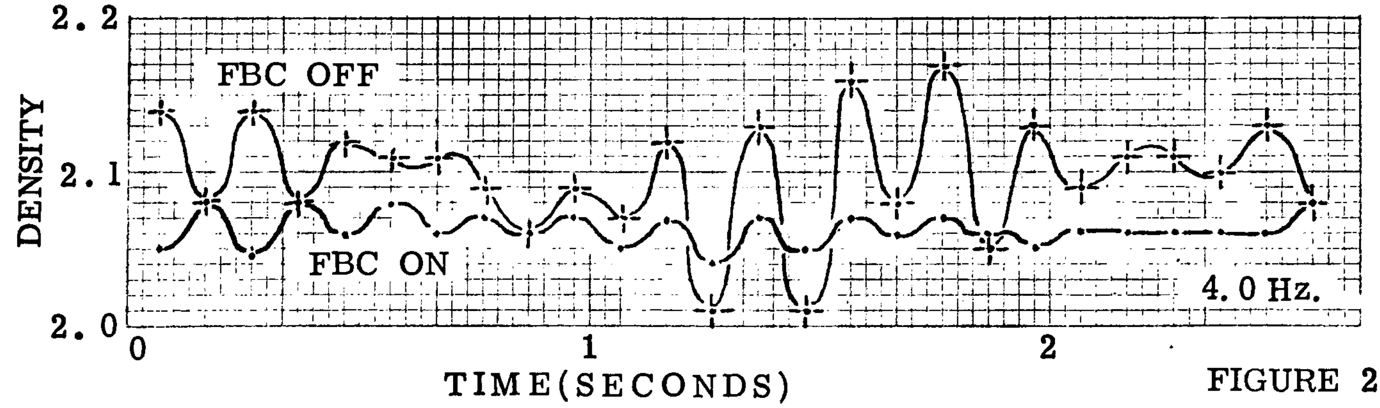


FIGURE 28

SINUSOIDAL DISTURBANCE . 010 INCH SOURCE SIZE

Step Function Disturbance Experiment

Curves 28-36 show the results of step function disturbances on the stabilized schlieren system. In each case the response is shown with and without the FBC system functioning (system on (.), system off (+)).

In every case as in the sinusoidal experiment, the density variation is reduced by FBC. The response of the system to a negative step (negative is defined as a flux cone shift which reduces the amount of flux passing over the knife edge) is generally more noticeable on the graph than a positive step. There are two reasons for this: first, the nonlinear nature of density, as indicated earlier, compresses responses in the positive direction, but, in addition, the FBC's detection system produces a greater response in the negative direction. This will be discussed under Further Work.

There is a lack of repeatability in some of the experimental data. This takes the form of variation in the amplitude of data between experimental runs. This variability was traced to a small amount of "sticktion" in the knife edge positioner pivots and some error in the set-up of 50% cutoff between runs. This should not affect the data relationship within each run because the set-up procedure was never performed during a run; therefore, system-on to system-off comparisons are valid.

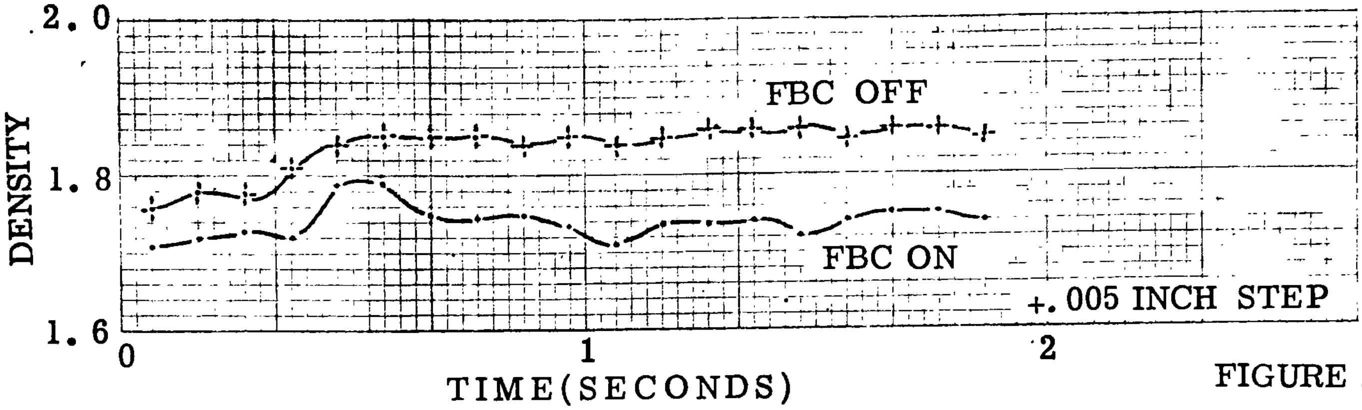


FIGURE 29

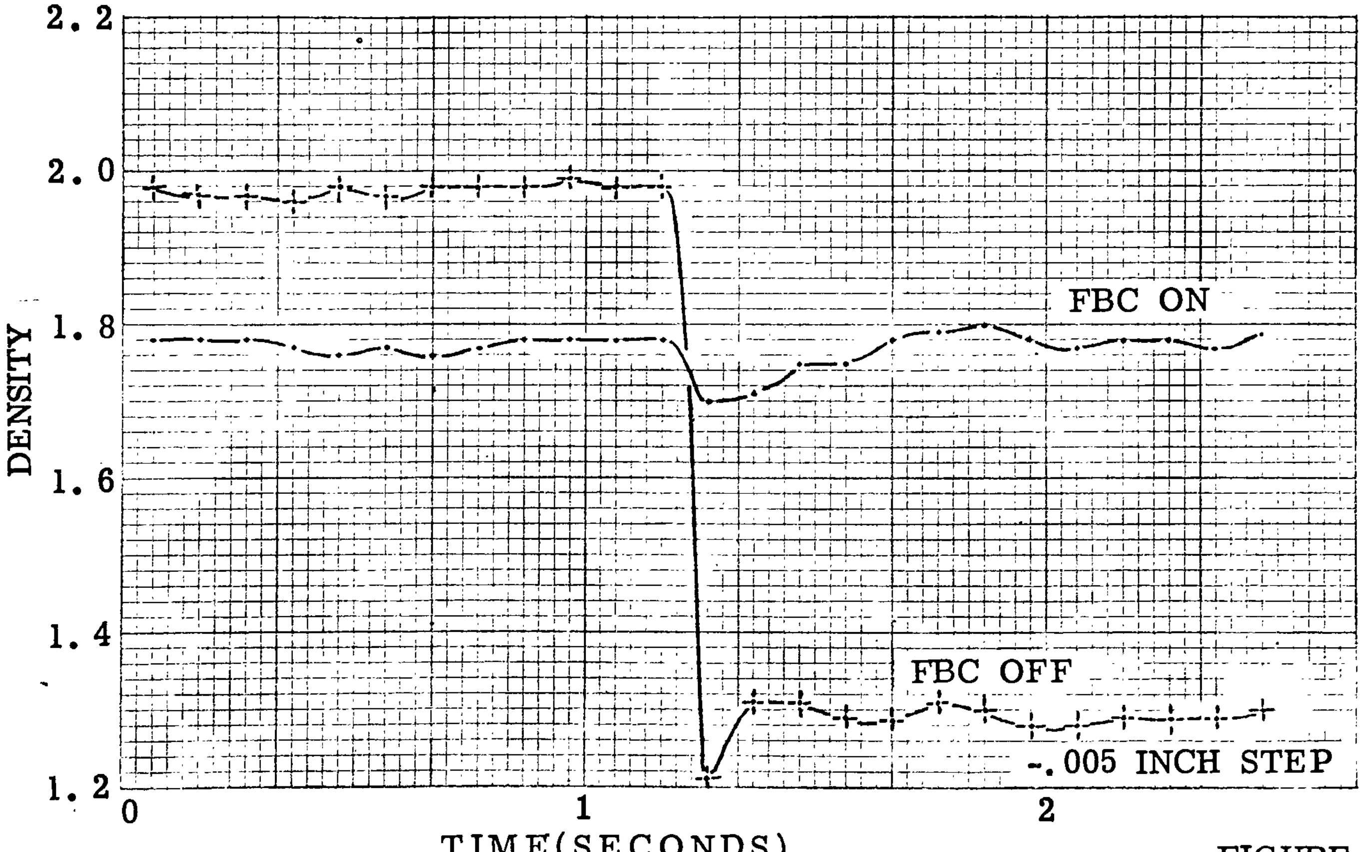


FIGURE 30

STEP FUNCTION DISTURBANCE .005 INCH SOURCE SIZE

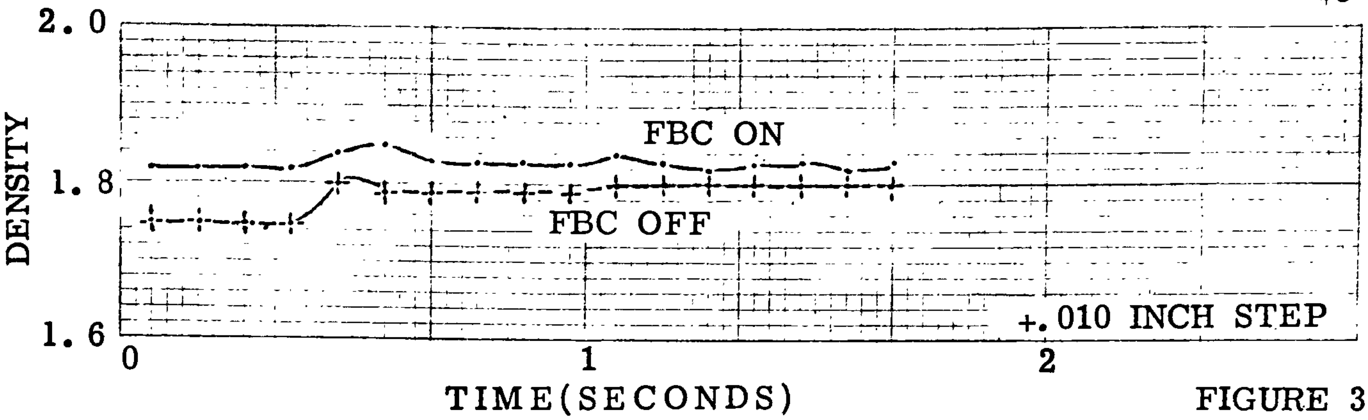


FIGURE 31

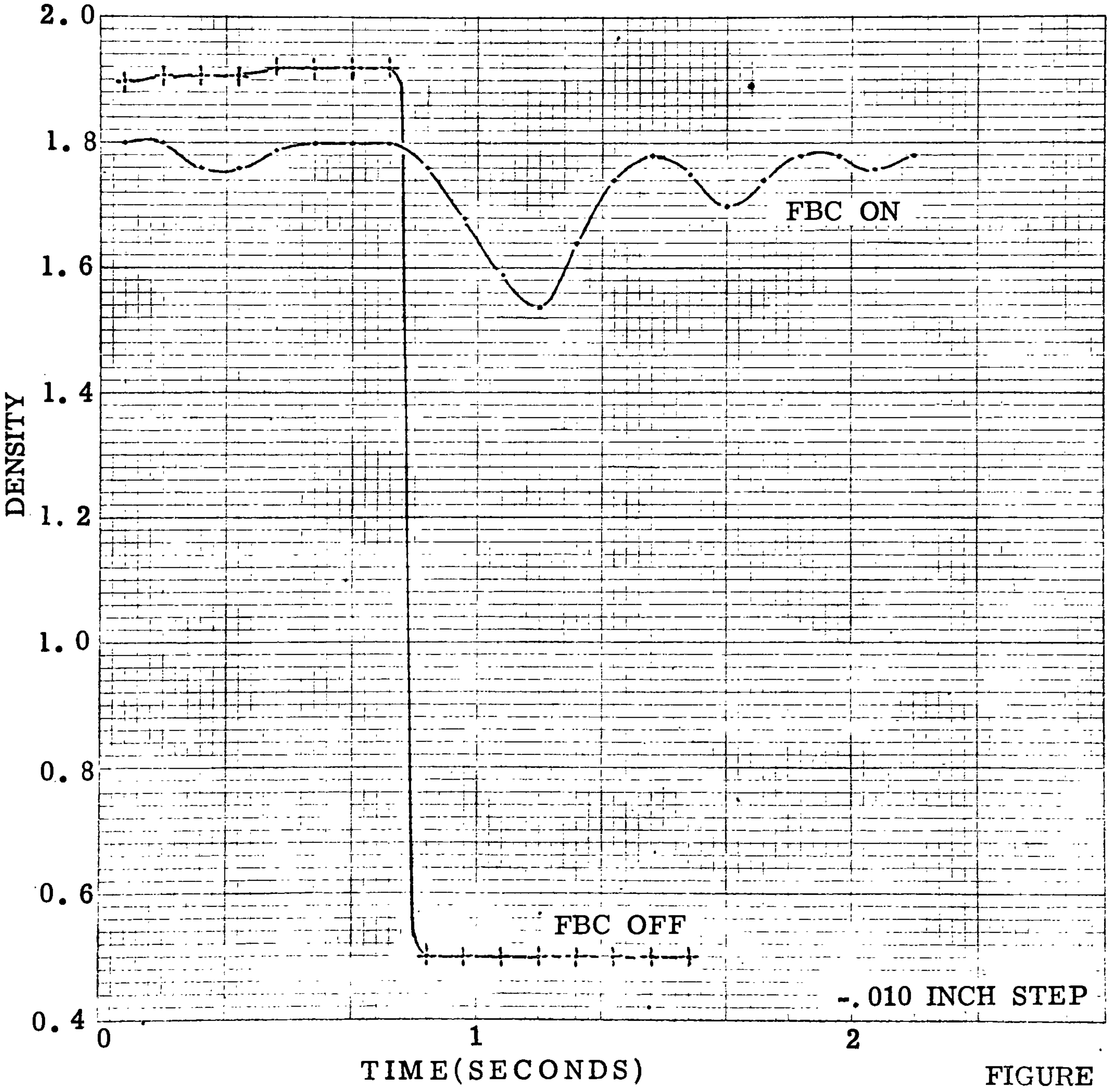


FIGURE 32

STEP FUNCTION DISTURBANCE .005 INCH SOURCE SIZE

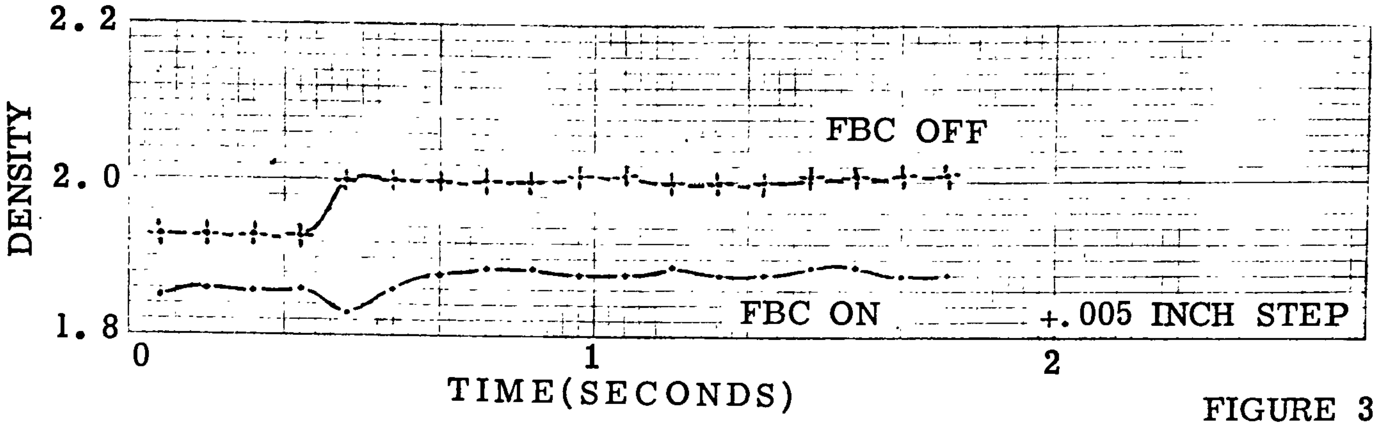


FIGURE 33

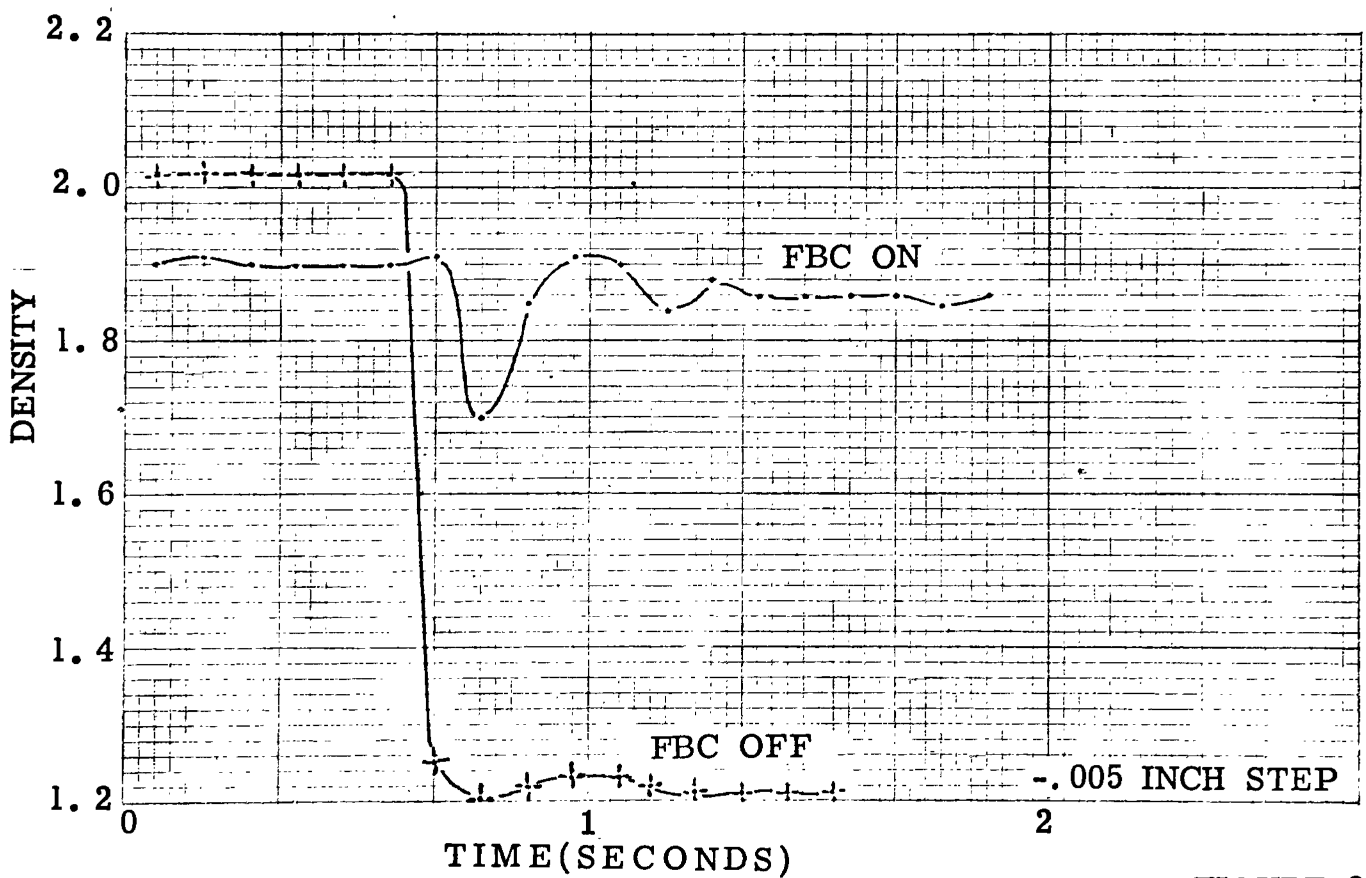


FIGURE 34

STEP FUNCTION DISTURBANCE .010 INCH SOURCE SIZE

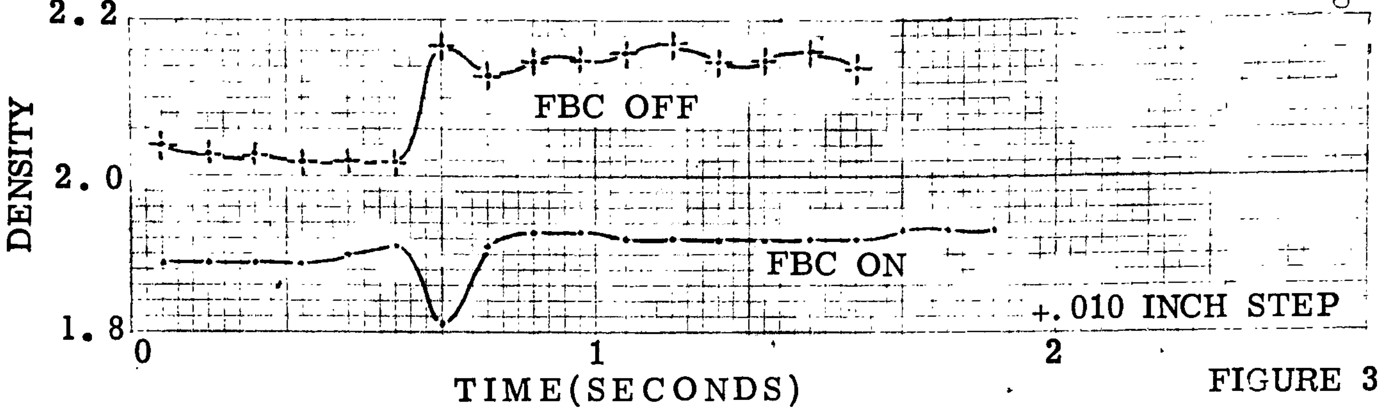


FIGURE 35

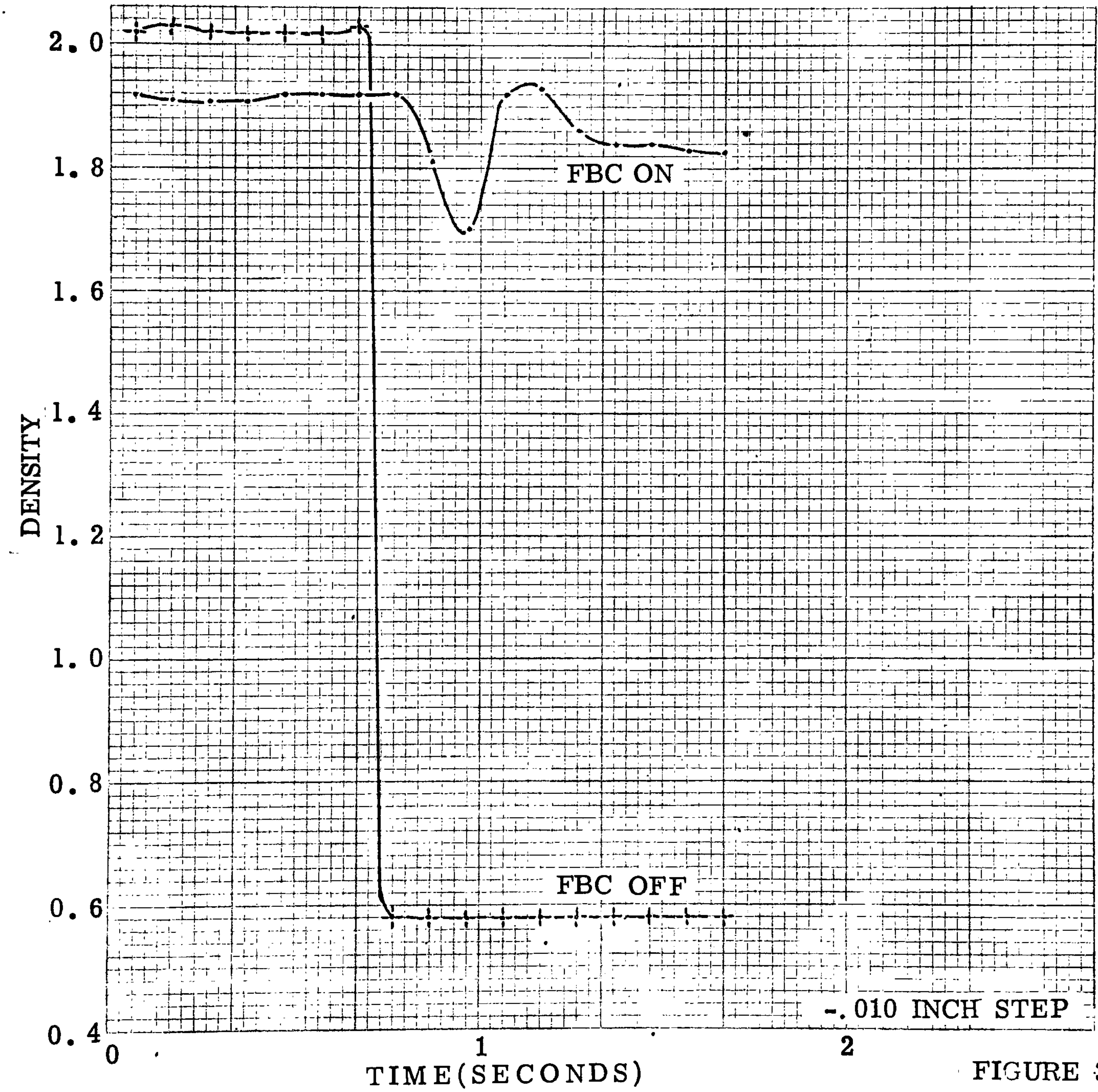


FIGURE 36

STEP FUNCTION DISTURBANCE .010 INCH SOURCE SIZE

Figure 37 shows a summary of the results of the two experiments in terms of approximate density variation for each set of conditions. In every case FBC produces an improvement in the stability of the schlieren system (indicated by decreased density variation).

SINUSOIDAL DISTURBANCE EXPERIMENT

	SCHLIEREN SYSTEM SOURCE SIZE .005 INCH		SCHLIEREN SYSTEM SOURCE SIZE .010 INCH	
	FBC SYSTEM ON	FBC SYSTEM OFF	FBC SYSTEM ON	FBC SYSTEM OFF
0.5 Hz ±0.006 INCH DEVIATION	0.06	1.53	0.03	0.26
1.0 Hz ±0.006 INCH DEVIATION	0.05	0.22	0.03	0.30
2.0 Hz ±0.006 INCH DEVIATION	0.08	1.12	0.05	0.23
4.0 Hz ±0.003 INCH DEVIATION	0.01	0.12	0.04	0.17

STEP INPUT DISTURBANCE EXPERIMENT

	SCHLIEREN SYSTEM SOURCE SIZE .005 INCH		SCHLIEREN SYSTEM SOURCE SIZE .010 INCH	
	FBC SYSTEM ON	FBC SYSTEM OFF	FBC SYSTEM ON	FBC SYSTEM OFF
+0.005 INCH STEP	0.04	0.08	0.02	0.07
+0.010 INCH STEP	0.02	0.05	0.03	0.13
-0.005 INCH STEP	0.02	0.57	0.04	0.80
-0.010 INCH STEP	0.06	1.40	0.07	1.44

FIGURE 37

CONCLUSION

The feedback control system in this experiment, though crude in construction, produced a marked increase in the stability of the schlieren system with which it was used. Further improvement of the design should increase its accuracy, frequency response, range and long term stability. With an improved FBC system the alignment maintenance of a schlieren system could be reduced to positioning the knife edge for an indicator null and an occasional check of the indicator to assure proper operation.

Further Work

In examination of the present system in retrospect several changes in the basic design become apparent. The primary area in need of improvement is the knife edge positioner; it should be redesigned to increase its linear range and frequency response. The second improvement involves the way in which cutoff is defined and the way in which the sensor system operated. As the system now stands the following is true: if the reference cell resistance is taken as R_r the resistance of the error cell can vary between $R_{r/2}$ and R_r for positive errors and between R_r and

$\gg R_r$ for negative errors. Thus the average current to the knife edge can only be 1/3 I_{max} (the instantaneous maximum current to the positioner) while it can be equal to I_{max} for negative errors. This causes a nonlinear sensitivity to errors which compounds the compression introduced by the nonlinear recording medium (photographic emulsion). This could be corrected by comparing the flux passing over the knife edge to that which does not. If this were done the unbalance conditions for negative and positive shifts would be symmetrical. A system of this type would require further optical design such as a mirror finish knife edge to allow the portion of the flux not passed to be measured.

BIBLIOGRAPHY

Dale, R. G., G.V. Ray, E.N. Freyling, and R.J. Haver, Semiconductor Power Circuits Handbook, (Motorola, 1968)

Davis, S. A., Servo-Mechanisms, (New York: Unitech, 1966)

Holder, D. W., and R. J. North, Schlieren Methods, (London: H. M. Stationary Office, 1963)

Kuo, B. C., Automatic Control Systems, (Englewood Cliffs, N. J.: Prentice-Hall, 1962)

Schardin, H., Schlieren Methods and Their Applications, "Die Schlierenverfahren und Hire Anwendungen", translated by E. Godwin, (London: Air Ministry, 1941)

Skilling, H. H., Electromechanics, (New York: John Wiley and Sons, Inc., 1962)

Sowa, W. A., and J. M. Toole, Special Semiconductor Devices, (New York: Holt, Rinehart and Winston, Inc., 1968)

Wells, C. B., Knife Edge Controller for a Schlieren System, (Applied Optics, V4, Pages 815-818, July 1965)